Memoirs of the Faculty of Engineering, Kyushu University, Vol. 56, No. 3, September 1996

Traffic Loading and Environmental Effects on Asphalt Pavement Rutting

by

David A. MFINANGA[1], Hidetoshi OCHIAI[2], Noriyuki YASUFUKU[3]

and Hiroshi YOKOTA[4]

(Received July 8, 1996)

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 out the separate effects of these two factors on asphalt pavement rutting. It is believed that this will lead to better modeling of pavement deterioration by clearly understanding and treating the two factors as separate entities. Pavement age is used to represent the cyclic effect of environmental forces. A methodology was devised to separate the two effects and analysis was carried out. Results show how each of these factors influence pavement rutting and provide an understanding of the influence of some of pavement parameters on pavement rutting.

Keywords: Pavement rutting, Pavement performance, Traffic loading effect, Environmental effect, Pavement deterioration.

1. Introduction

Roads have provided one of the most important means of transport. In the past decades, there has been an increase in the number of roads/highways constructed worldwide. Management of roads, including providing routine maintenance, rehabilitation, or reconstruction, has therefore become more important. Since the amount of funds allocated for such activities are limited, Pavement Management Systems (PMS) were developed to optimize resource use. In short, a PMS is a systematic approach to providing highway administrators and engineers with the types of information needed to effectively and efficiently manage their highway pavements[1)]. To develop a balanced program for highway network, the rate of deterioration of the pavement needs to be predicted. Prediction models provide parameters to pavements management optimization so that they can base the selection of future maintenance, rehabilitation, and reconstruction programs on the forecasted conditions.

Many people in the field of pavement performance have stated that one of the largest

[1] Graduate Student, Department of Civil Engineering
[2] Professor, Department of Civil Engineering
[3] Associate Professor, Department of Civil Engineering
[4] Professor, Miyazaki University

deficiencies is the absence of an accurate understanding of pavement distress progression in relation to causal factors such as traffic loading, environment, and others. It is acknowledged that pavements deteriorate with traffic, time, and environment. However, the separate or interacting effects of these components are not clearly defined at the present time, especially with regard to age or environment. Many reseachers 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. The poor performance of even the more realistic specifications indicates that there is a problem with the traditional approaches used to model the deterioration of highway pavements[2]. This research was aimed at studying how pavement distress (rutting) develops 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 gave an insight on the effect of traffic loading but since its sections survived only one or two years, the test results do not indicate the long-term effect of environmental factors. Its report concluded that the effects of environment need to be studied and encouraged research into the mechanical and physical laws involved in pavement performance in order to realize rational mathematical models by which performance can be related to the fundamental properties of materials and to the dynamic characteristics of the loading. It suggests that since completion of such research work appears to be years away, immediate attention should also be given to means for extending the empirical models developed at the test to include additional important parameters[3]. Heeding this advice, this research aims at improving modeling by introducing environmental factor as a separate entity. Furthermore, it is hoped that results obtained here could somehow help in understanding the much required mechanical mechanism.

2. General Approach

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 factors. Although there are many models already developed that use the age parameter, in such models it rather represents traffic loading. This is so because the parameter is usually applied to pavements with approximately same traffic loading. The age parameter used in this research represents the pure environmental effect.

Due to correlation between distresses, it is only practical to predict distinct distresses. Fatigue, permanent deformation, and thermal cracking are the three major modes of distress that lead to reduction in serviceability of AC pavements[4]. For these reasons, pavement rutting and cracking, which are the two main distresses used in deciding rehabilitation, will mainly be modeled. However, this paper covers pavement rutting only.

Individual distresses have been chosen for the study because this will actually lead to the understanding of a certain type of distress progression as opposed to average indices that combine several distresses. Furthermore, distress indices are typically obtained by averaging various distress attributes with proper weight factors, e. g. CPI or OPI. Hence, the value alone does not allow the examination of various distress types nor does it reflect the true condition of the pavement[5]

Pavements are complex physical structures responding in a complex way to the influences of numerous environmental and load-related variables, others, and their interactions. An all inclusive approach is so highly complex that a compromise procedure is required. The modeling here, while aiming at actually finding the separate effects of traffic loading and environment, has been kept simple to include mainly factors perceived to be important. It is believed here that, if the assumed deterioration trend is correct, the number of variables is of secondary consideration.

3. Methodology

3.1 Separation of Traffic Loading and Environmental Effects

As was previously mentioned, pavement age was 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. Therefore, the analysis here is aimed at finding rutting progression due to environmental effects rather than the effect of different climatic or environmental conditions. 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*). 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.

3.2 Pavement Structural Strength

The Japanese method of pavement design is based on the AASHO Road Test concept. It calculates the required equivalent pavement thickness, T_A, using design subgrade *CBR* and cumulative 10 ton equivalent axle loads (*EAL*). The equivalent pavement thickness is then used to calculate individual layer thicknesses using layer coefficients[6].

All the expressway pavements whose data were used had a 10 cm surface-and-binder course, an asphalt-treated base, and a granular subbase as shown in **Fig. 3.1**. Different thicknesses of base and subbase layers together with defferent subgrade *CBR* values resulted in pavements with different structural strengths. Granular materials for the subbase included decomposed weathered granite, sandstone, etc. The top 1m of the subgrade consisted mostly of borrowed material ranging from decomposed granite, crushed stone, mixed sand-gravel, to clay.

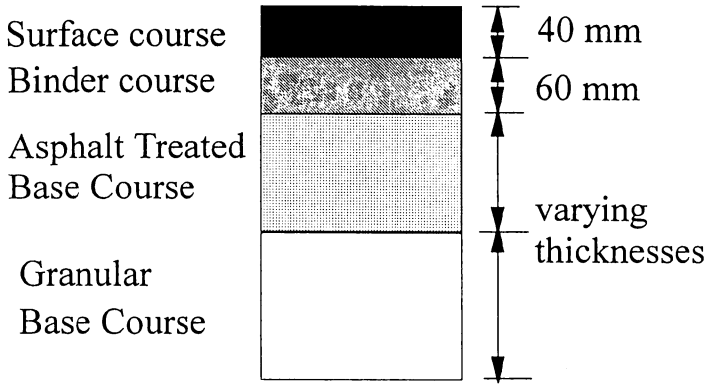


Fig. 3.1 Typical Pavement Cross-Section

Table 3.1 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

To eliminate the influence of pavement structural strength, analysis was done on data from road sections with similar structural strengths. This led to the division of all pavements into 4 structural groups according to T_A and *CBR* as shown in **Table 3.1**. As in any analysis based on historical data, the groups were formed as the data were available and not by pure choice. However, care was taken to have enough data in each group to enable proper 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.

4. Environmental Factor

There are two main environmental factors, temperature and rainfall, with regard to pavement performance. Temperature will affect (1) the creep properties of asphalt concrete, (2) thermal-induced stresses in asphalt concrete, (3) freezing and thawing of the roadbed soil. The major effect is with regard to the thaw-weakening which can occur during the spring thaw period. A second effect of freezing is the occurrence of frost heaving, causing a reduction in the serviceability of the pavement. The climatic factors of air temperature, solar radiation received at the surface, wind, and precipitation are major parameters that affect the severity of frost effects in a given geographical area[7]. Spring deflection measurements at the AASHO Road Test suggest a retained modulus 80-85% of the normal one obtained during summer or fall[8]. In addition to the seasonal effect on the subgrade and granular materials, temperature will also influence the characteristics of the AC and performance will be affected in 3 ways: (1) low temperature craking, (2) fatigue cracking, and (3) rutting[7].

Rainfall, if allowed to penetrate the pavement structure or roadbed soil, will influence the properties of those materials. Water enters the pavement structure in many ways, such as through cracks, joints, or pavement infiltration, or as groundwater from interrupted aquifer, high water table, or localized spring. Effects of this water on pavement include: (1) reduced strength of unbound granular materials, (2) reduced strength of roadbed soils, and (3) pumping of fines in aggregate base under flexible pavements with resulting loss of support[7]. The internal moisture due to water trapped in slow draining pavements and base can increase the rate of deterioration by hundreds to thousands of times greater than when water is not present. Moisture infiltration into the compacted clay subgrade results in a reduction in the shear strength of the soil which makes the subgrade weaker and more susceptible to pavement deterioration, such as alligator cracking and rutting[9]. There is also an argument

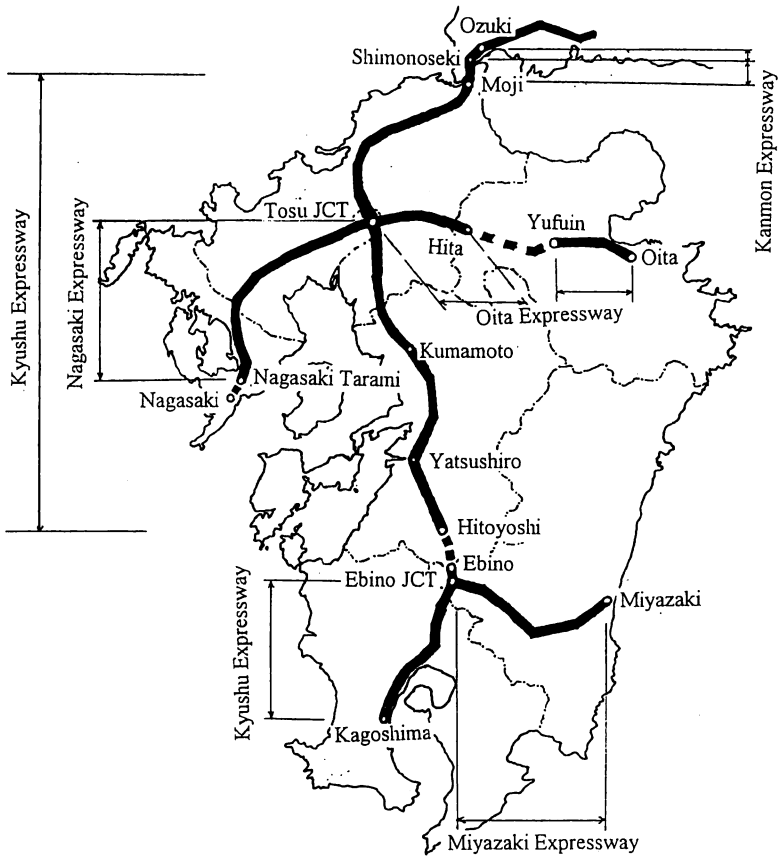
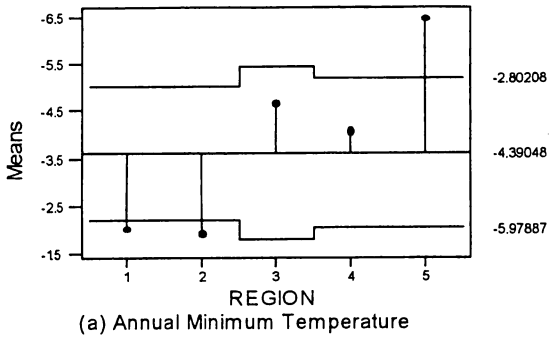


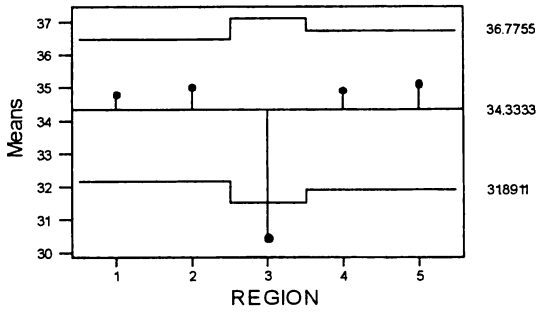
Fig. 4.1 Kyushu Expressways

as to whether aging strengthens the pavement or weakens it by making it brittle.

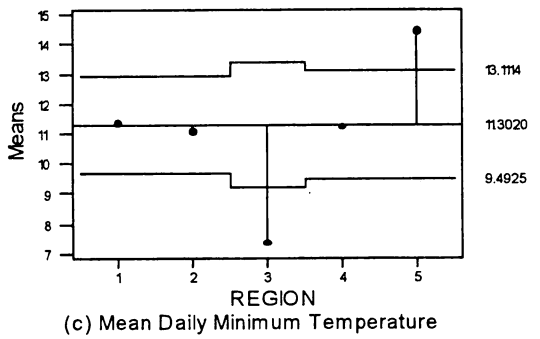
The above discussion attests to the scientific and experience proof of the effect of environmental factors on pavement rutting. As was mentioned in sec. 3, this research is mainly exploring the cyclic effect of environmental forces rather than the effect in places with different environmental conditions. For this purpose, age is used to represent environmental forces. Since it was necessary to use pavement data of places with same climatic condition, data from Kyushu island, whose different regions do not have significant climatic differences, was used. **Fig. 4.1** which shows expressways in Kyushu whose data were used, shows the 5 regions (in total there are 6 regions). Only weather information from 1989 to 1993, the time when most of the survey were carried out, was available and most detailed. A more critical analysis resulted in **Fig. 4.2** which shows the analysis of means for temperatures and rainfall for the 5 regions at a confidence level of $\alpha = 0.05$. The number of wet days in a year (>0.5mm) and annual rainfall amount were relatively the same for all the regions. On the temperature side, Fukuoka and Kagoshima regions showed little but not significant deviations. Important two years data were lacking for Fukuoka and the location of its weather station, which is too high to represent regional conditions, is controversial. Also, main effects analysis showed that, year 1990 whose data were missing for Fukuoka, was very influential as it was exceptionally hot. Kagoshima region has a little but not significantly warmer climate. From soil condition records, the groundwater conditions were assumed to be the same. The different regions therefore do not have significant environmental difference.



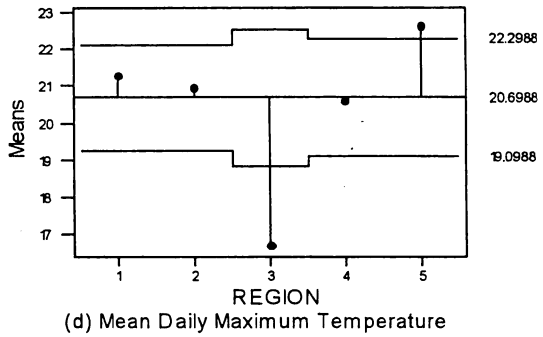
(a) Annual Minimum Temperature



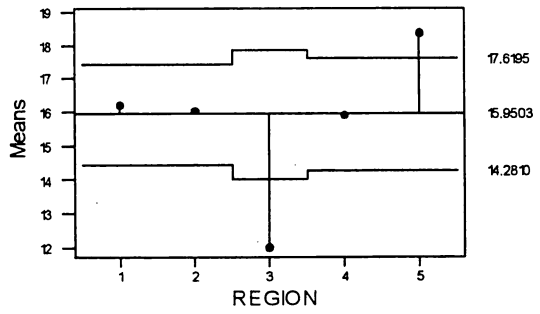
(b) Annual Maximum Temperature



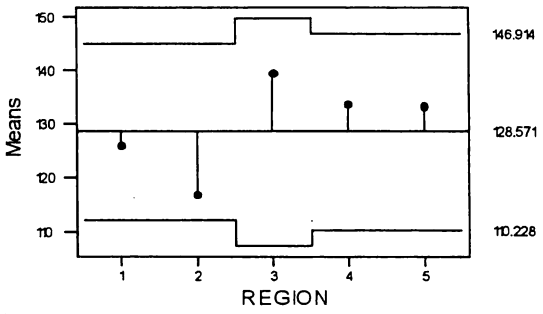
(c) Mean Daily Minimum Temperature



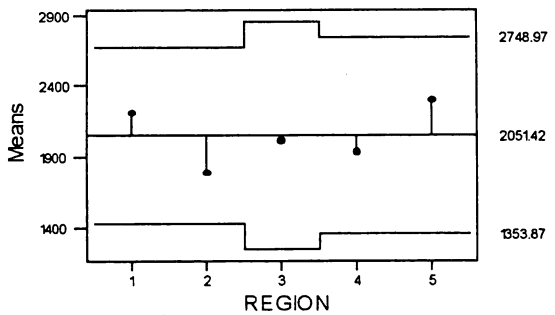
(d) Mean Daily Maximum Temperature



(e) Mean Daily Temperature



(f) Annual Number of Wet Days (Prep.>0.5 mm)



(g) Annual Rainfall (mm)

REGIONS
1 MIYAZAKI
2 KUMAMOTO
3 FUKUOKA
4 NAGASAKI
5 KAGOSHIMA

TEMP. IN DEGREES CENTIGRADE

Fig. 4.2 Regional Climates: Analysis of Means

5. Description of Data

5.1 Rutting

A rut is a surface depression in the wheel paths. Rutting stems from a permanent deformation in any of the pavement layers or subgrade, usually caused by consolidation or lateral movement of the materials due to traffic loads. Rutting may also be caused by plastic movement in the mix in hot weather or inadequate compaction during construction[7]. It has long been considered a measure of performance of flexible pavements, and its characteristics can be used as an indication of structural deterioration and road surface deformation[7),10),11)]. 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.

Accurate measurement of pavement distress is very important, without which the PMS would become unreliable. Though most methods aim at measuring the mean rut depth, there is neither a single, widely accepted method nor international standardization. The rut measurement method used by Japan Highway Corporation (JH), which overseas all the expressways in Japan, was used here. Rut depths are automatically measured by an automobile and are decided as shown in **Fig. 5.1** obtaining an average for each 100 m section. According to JH policies, a rut depth more than 20 mm requires remedy.

Fig. 4.1 shows Kyushu expressways (total length of 600 km) whose pavements condition data were used in the analysis. **Table 5.1** depicts all the expressways, sections, their time of construction, the survey time and their ages at the time. There were pavements constructed as far back as 1971 and the first survey (whose records were available) was done in 1988. Available data was for the surveys conducted in 1988, 1990, 1991, 1992, and 1993. Data available for analysis spanned about 20 years.

5.2 Traffic Data

Researchers have long related pavement rutting (permanent deformation) in asphalt pavements with repetitive application of traffic loading. The accurate collection and calculation of cumulative *EAL* is of therefore paramount importance. Cumulative one-way traffic from construction to the time of each condition survey was calculated for all sections. Unlike the U. S. and U. K. which use 8.16 ton, the standard single axle load in Japan is 10 ton. Long-term and countrywide research conducted in Japan found that a factor of 0.85 could be

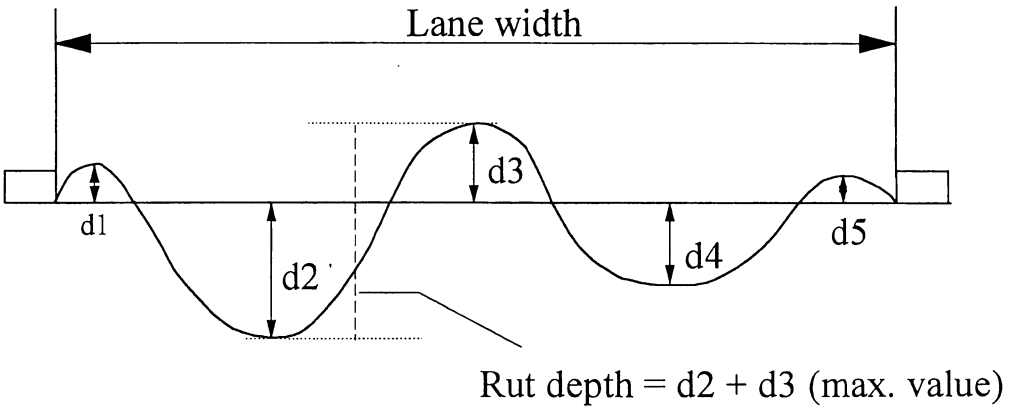


Fig. 5.1 Rut Depth Measurement

Table 5.1 Road Sections

HIGHWAY	ROAD SECTION	L (km)	CONST MM/YY	AGE AT INDICATED TIME OF SURVEY				
				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~TOSU(J)	16.0						
	TOSU(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							

used to convert traffic (i. e. ordinary freight trucks and buses) into 10 tf axle loads[12]. The 10 tf cumulative *EAL* ranged from 30,000 to 13,000,000, providing a wide range for analysis.

6. Data Preparation and Screening

Since this study is aimed at finding the effects of traffic loading and environment, it was necessary to use rut depth data of pavements before rehabilitation to avoid trend distortion. This reduced the number of data (rut depths for a section on different surveys) that could be used to 32,044. Some pavement condition data and rehabilitation information were missing which further reduced the amount of data available.

Screening of data was a great challenge especially in the case of pavement rutting. As was observed in the AASHO Road Test which measured rut depth serially, although in overall rutting eventually increases with loading, it does not increase monotonically. **Fig. 6. 1** shows a typical case of rut depth vs *EAL* in the AASHO Road Test. In such shifting tendencies of increasing and decreasing rut depths, rut depths throughout the survey years had to be observed. A reduced rut depth in one or two years was no longer a proof of rehabilitation or any suspicion. In cases where there was a big reduction in rut depth and no rebound in subsequent years, such data were left out. It was assumed that rehabilitation, not in record, had been carried out or there were some errors in recording. This further reduced the amount of reliable available data for analysis to 11,000.

Grouping of data for effect of traffic loading analysis resulted into different age groups containing pavements with different *EAL* as shown in **Table 6.1(a)**. There were some data which fell under age groups with too few data that use couldn't be made of them. Leaving out such data reduced available data for this analysis to 9,114. For the analysis of environmental effect, pavements were grouped into groups of same *EAL* ranges as shown in **Table 6.1(b)**. Again since some pavements had *EAL* which put them in groups with very few data, they could not be used. This reduced data available for the analysis of effect of environment to 8,781. Overlapping in *EAL* ranges and therefore reuse of same data was employed to increase the number of cases for analysis. It can also be noticed that in some *EAL* groups in structural groups C & D, traffic loading (*EAL*) range was much wider. This was necessary because pavements in groups C & D had heavier traffic. For each stretch of road with either same age (in the case of analysis of traffic loading effect) or traffic loading (in case of analysis of effect of environment), a representative average rut depth was calculated after

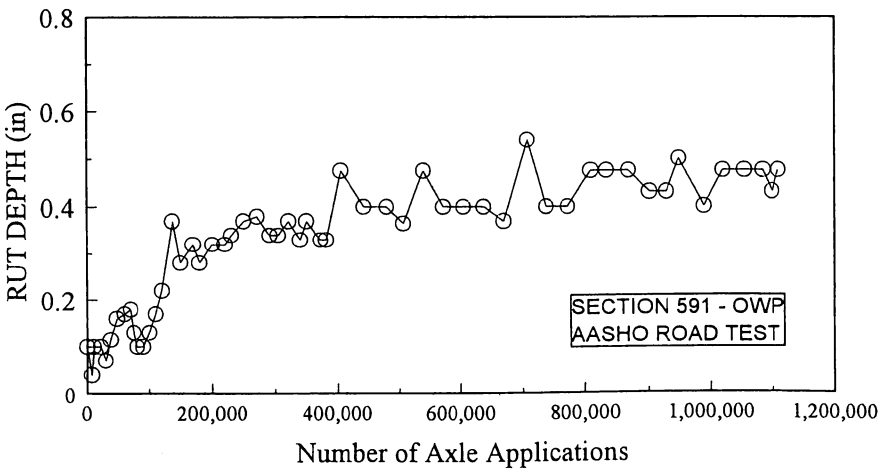


Fig. 6.1 Rut Depth vs EAL for sec. 591, AASHO Road Test [14]

Table 6.1(a) Grouped Sections Data for the Analysis of Effect of Traffic Loading

STR GR	AGE GR.	AGE (Yrs)	HIGHWAY	SECTION KMPOST	EAL (I-way)	A-DIRECTION NO. OF DATA	A-DIRECTION RUT (mm)	D-DIRECTION NO. OF DATA	D-DIRECTION RUT (mm)
A	6-7	5.5	NAGASAKI	15.8−26.6	1,119,392	12	17.8	11	12.4
		6.0	NAGASAKI	104.0−108.9	172,602	37	7.7	37	7.3
		6.0	NAGASAKI	91.9−104.0	186,225	89	8.2	93	8.5
		6.5	OITA	10.9-19.0	711,903	76	8.5	76	10.1
		6.5	OITA	4.9-10.9	930,828	56	9.7	56	10.8
		7.0	MIYAZAKI	70.0-82.5	343,781	112	10.0	114	10.8
		7.0	MIYAZAKI	48.9-70.0	352,668	187	9.8	188	9.8
	8-10	7.5	MIYAZAK	28.5-48.9	319,121	189	10.1	189	10.6
		8.0	NAGASAKI	104.0-108.9	303,720	8	6.9	7	6.1
		8.0	MAGASAKI	91.9-104.0	371,768	22	6.5	17	6.9
		9.0	MIYAZAKI	70.0-82.5	493,771	32	9.4	15	10.3
		9.0	MIYAZAKI	48.9-70.0	507,821	76	9.3	103	9.8
		9.5	MIYAZAKI	28.5-48.9	473,087	95	8.9	98	10.0
		10.0	NAGASAKI	104.0-108.9	521,133	9	8.3	14	7.6
	11-12	11.0	MIYAZAKI	70.0-82.5	680,669	54	11.4	31	12.7
		11.0	MIYAZAKI	48.9-70.0	705,439	95	11.5	96	12.3
		11.0	NAGASAKI	104.0-108.9	645,551	12	8.5		
		11.5	MIYAZAKI	28.5-48.9	668,542	130	11.0	110	12.8
		12.0	MIYAZAKI	70.0-82.5	789,773	41	10.7	15	11.7
		12.0	MIYAZAKI	48.9-70.0	821,376	96	12.5	86	11.6
B	3-5	2.5	KYUSHU-A	20.2-31.3	2,106,711	46	11.4	46	9.3
		3.5	NAGASAKI	68.6-78.4	607,988	98	8.5	98	8.1
		3.5	NAGASAKI	64.1-68.6	629,660	45	8.5	45	9.3
		3.5	NAGASAKI	78.4-91.9	621,663	135	10.0	135	9.9
		3.5	NAGASAKI	52.8-64.1	758,168	113	8.9	113	9.1
		4.5	KYUSHU-A	20.2-31.3	3,976,561	35	10.5	45	12.6
		5.5	KYUSHU-B	67.4-71.8	294,212	28	8.3	28	8.2
		5.5	KYUSHU-A	20.2-31.3	4,929,680	34	11.5	32	10.7
	9-11	8.5	KYUSHU-B	15.7-21.7	322,470	58	8.9	58	8.7
		8.5	KYUSHU-B	21.7-35.5	355,853	136	10.9	136	9.1
		9.0	KYUSHU-B	2.0-15.7	380,771	53	8.8	39	7.9
		9.0	KYUSHU-B	0.0-2.0	543,684	8	10.0		
		10.5	KYUSHU-B	15.7-21.7	523,008	15	7.9	12	7.5
		10.5	KYUSHU-B	21.7-35.5	561,215	11	10:1	27	8.5
		11.0	KYUSHU-B	2.0-15.7	643,023	30	11.7	30	10.3
	12-13	12.0	KYUSHU-B	2.0-15.7	793,989	21	12.0	19	10.8
		12.5	KYUSHU-B	21.7-35.5	848,779	29	11.8	17	9.3
		13.5	KYUSHU-B	21.7-35.5	1,010,657	13	11.8		
C	5-6	4.5	KYUSHU-A	0.0-13.3	757,786	132	11.6	133	10.8
		4.5	NAGASAKI	41.7-52.8	816,838	89	9.0	89	7.1
		4.5	NAGASAKI	26.6-41.7	967,493	117	8.6	117	7.8
		4.5	KYUSHU-A	13.3-20.2	3,920,409	69	10.5	69	10.3
		5.5	KYUSHU-A	13.3-20.2	4,867,631	64	11.1	64	11.0
		5.5	NAGASAKI	41.7-52.8	1,384,205	89	11.7	89	10.7
		5.5	NAGASAKI	26.6-41.7	1,614,044	116	10.9	116	10.8
		5.5	KYUSHU-A	0.0-13.3	2,393,286	111	14.2	111	12.0
	9-12	8.5	KYUSHU-A	0.0-13.3	4,227,014	87	15.9	113	16.0
		9.5	KYUSHU-A	0.0-13.3	4,449,161	51	15.8	43	15.3
		11.0	KYUSHU-B	60.5-67.1	260,069	66	10.3	66	11.6
		12.5	MIYAZAKI	17.9-28.5	345,039	105	9.5	105	9.3
		12.5	MIYAZAKI	2.0-17.9	358,236	152	9.7	56	9.9
		12.5	KYUSHU-B	60.5-67.1	466,658	12	10.3	22	11.8
	15-16	14.5	MIYAZAKI	17.9-28.5	502,139			7	7.4
		15.0	KYUSHU-B	51.9-60.5	818,553	55	11.1	55	9.5
		15.0	KYUSHU-B	43.2-51.9	840,007	44	10.6	83	10.6
		15.0	KYUSHU-B	60.5-67.4	770,979	12	10.3	22	11.8
		16.0	KYUSHU-B	60.5-67.4	966,861			7	13.0
		16.0	KYUSHU-B	35.5-43.2	1,291,841			15	8.9
		16.0	KYUSHU-A	135.0-146.6	4,413,503	69	14.6	47	15.9
D	9-10	8.5	KYUSHU-A	195.1-213.5	1,591,952	171	12.3	171	11.7
		9.5	KYUSHU-A	31.3-45.2	5,970,576			32	15.3
		10.0	KYUSHU-A	183.1-195.1	2,241,505	83	13.4	83	12.4
	11-12	10.5	KYUSHU-A	195.1-213.5	2,170,887	54	12.2	68	11.0
		11.0	KYUSHU-A	45.2-57.7	5,964,579	13	14.8	10.5	20.0
		11.5	KYUSHU-A	31.3-45.2	8,073,636	11	15.9	41	17.3
		12.0	KYUSHU-A	171.2-183.1	2,758,217	117	13.2		
		12.0	KYUSHU-A	183.1-195.1	2,994,926	45	14.5	45	12.9
		12.5	KYUSHU-A	195.1-213.5	2,912,787	99	14.5	98	13.4
	14-15	13.5	KYUSHU-A	195.1-213.5	3,309,099	48	14.7	58	13.6
		13.5	KYUSHU-A	31.3-45.2	10,440,304			16	20.5
		14.0	KYUSHU-A	183.1-195.1	3,925,513	46	17.5	44	16.1
		15.0	KYUSHU-A	96.0-105.4	5,419,993	74	16.8	35	18.7
		15.0	KYUSHU-A	183.1-195.1	4,418,322	32	17.3	30	16.7
		15.0	KANMONKYO	544.4-549.5	6,637,446	35	16.4	35	16.1

*DIRECTION is defined as Ascending (A)-towards Tokyo or Descending (D)-away from Tokyo

Table 6.1(b) Grouped Sections Data for the Analysis of Environmental Effect

STR GR.	EAL GROUP	EAL (One-way)	HIGHWAY	SECTION KMPOST	AGE (Yrs)	A-DIRECTION NO. OF DATA	A-DIRECTION RUT (mm)	D-DIRECTION NO. OF DATA	D-DIRECTION RUT (mm)
A	600,000-	645,551	NAGASAKI	104.0-108.9	11.0	12	8.5	13	8.1
	800,000	668,542	MIYAZAKI	28.5-48.9	11.5	130	11.0	100	12.8
		680,669	MIYAZAKI	70.7-82.5	11.0	54	11.4	31	12.7
		705,439	MIYAZAKI	48.9-70.0	11.0	95	11.5	96	12.3
		711,903	OITA	10.9-19.0	6.5	76	8.5	76	10.1
		714,135	NAGASAKI	91.9-104.0	10.0	29	7.9	30	8.4
		776,181	MIYAZAKI	28.5-48.9	12.5	78	12.8	80	13.7
		789,773	MIYAZAKI	70.0-82.5	12.0	41	10.7	15	11.7
	700,000-	705,439	MIYAZAKI	48.9-70.0	11.0	95	11.5	96	12.3
	900,000	711,903	OITA	10.9-19.0	6.5	76	8.5	76	10.1
		714,135	NAGASAKI	91.9-104.0	10.0	29	7.9	30	8.4
		776,181	MIYAZAKI	28.5-48.9	12.5	78	12.8	80	13.7
		789,773	MIYAZAKI	70.0-82.5	12.0	41	10.7	15	11.7
		821,376	MIYAZAKI	48.9-70.0	12.0	86	11.6	96	12.5
		910,693	NAGASAKI	91.9-104.0	11.0	31	8.6	28	9.4
		930,828	OITA	4.9-10.9	6.5	56	9.7	56	10.8
	800,000-	821,376	MIYAZAKI	48.9-70.0	12.0	86	11.6	96	12.5
	1,000,000	930,828	OITA	4.9-10.9	6.5	56	9.7	56	10.8
		1,119,392	NAGASAKI	15.8-26.6	5.5			12	12.5
B	400,000-	545,684	KYUSHU-B	0.0-2.0	9.0	8	10.0		
	600,000	561,215	KYUSHU-B	21.7-35.5	10.5	11	10.1	27	8.5
		607,988	NAGASAKI	68.6-78.4	3.5	98	8.5	98	8.1
	500,000-	545,684	KYUSHU-B	0.0-2.0	9.0	8	10.0		
	700,000	561,215	KYUSHU-B	21.7-35.5	10.5	11	10.1	27	8.5
		607,988	NAGASAKI	68.6-78.4	3.5	98	8.5	98	8.1
		621,663	NAGASAKI	78.4-91.9	3.5	135	10.0	135	9.9
		629.660	NAGASAKI	64.1-68.6	3.5	45	8.5	45	9.3
		643,023	KYUSHU-B	2.0-15.7	11.0	30	11.7	30	10.3
	600,000-	621,663	NAGASAKI	78.4-91.9	3.5	135	10.0	135	9.9
	800,000	629,660	NAGASAKI	64.1-68.6	3.5	45	8.5	45	9.3
		643,023	KYUSHU-B	2.0-15.7	11.0	30	11.7	30	10.3
		758,168	NAGASAKI	52.8-64.1	3.5	113	8.9	113	9.1
		793,989	KYUSHU-B	2.0-15.7	12.0	21	12.0	19	10.8
C	600,000-	669,034	KYUSHU-B	35.5-43.2	12.0	70	7.6	68	9.7
	800,000	770,979	KYUSHU-B	60.5-67.4	15.0	12	10.3	22	11.8
		816,838	NAGASAKI	41.7-52.8	4.5	89	9.0	89	7.1
		818,553	KYUSHU-B	51.9-60.5	15.0	55	9.5	55	11.1
	800,000-	816,838	NAGASAKI	41.7-52.8	4.5	89	9.0	89	7.1
	1,000,000	818,553	KYUSHU-B	51.9-60.5	15.0	55	9.5	55	11.1
		840,007	KYUSHU-B	43.2-51.9	15.0	44	11.0	83	10.6
		966,861	KYUSHU-B	60.5-67.4	16.0	4	11.5	7	13.0
		967,493	NAGASAKI	26.6-41.7	4.5	117	8.6	117	7.8
	1,400,000-	1,384,205	NAGASAKI	41.7-52.8	6.5	89	11.7	89	10.7
	2,400,000	1,498,402	KYUSHU-B	35.5-43.2	16.0	20	11.5	15	13.5
		1,614,044	NAGASAKI	26.6-41.7	6.5	116	10.9	116	10.8
		2,062,114	KYUSHU-A	13.3-20.2	2.5	69	7.7	69	7.5
		2,393,286	KYUSHU-A	0.0-13.3	6.5	114	14.2	111	12.0
	4,200,000-	4,227,014	KYUSHU-A	0.0-13.3	8.5	87	15.9	113	16.0
	4,800,000	4,413,503	KYUSHU-A	135.0-146.6	16.0	69	14.6	47	15.9
		4,449,161	KYUSHU-A	0.0-13.3	9.5	51	15.8	43	15.2
		4,867,631	KYUSHU-A	13.3-20.2	5.5	62	11.1	69	11.0
D	1,500,000	1,591,952	KYUSHU-A	195.1-213.5	8.5	171	12.3	170	11.7
	3,000,000	2,170,887	KYUSHU-A	195.1-213.5	10.5	54	12.2	69	11.0
		2,241,505	KYUSHU-A	183.1-195.1	10.0	83	13.4	83	12.4
		2,758,217	KYUSHU-A	171.2-183.1	12.0	117	13.2	2	12.0
		2,912,787	KYUSHU-A	195.1-213.5	12.5	99	14.5	98	13.4
	2,000,000-	2,170,887	KYUSHU-A	195.1-213.5	10.5	54	12.2	69	11.0
	3,500,000	2,241,505	KYUSHU-A	183.1-195.1	10.0	83	13.4	83	12.4
		2,758,217	KYUSHU-A	171.2-183.1	12.0	117	13.2	2	12.0
		2,912,787	KYUSHU-A	195.1-213.5	12.5	99	14.5	98	13.4
		2,994,926	KYUSHU-A	183.1-195.1	12.0	45	14.5	45	12.9
		3,309,099	KYUSHU-A	195.1-213.5	13.5	48	14.7	58	13.6
	4,000,000-	3,925,513	KYUSHU-A	183.1-195.1	14.0	46	17.5	44	16.1
	6,000,000	4,418,322	KYUSHU-A	183.1-195.1	15.0	32	17.3	30	16.7
		5,419,993	KYUSHU-A	96.0-105.4	15.0	74	16.8	35	18.7
		5,964,579	KYUSHU-A	45.2-57.7	11.0	13	14.8		
		5,970,576	KYUSHU-A	31.3-45.2	9.5	12	12.3	32	15.3
	5,500,000-	5,419,993	KYUSHU-A	96.0-105.4	15.0	74	16.8	35	18.7
	6,500,000	5,964,579	KYUSHU-A	45.2-57.7	11.0	13	14.8		
		5,970,576	KYUSHU-A	31.3-45.2	9.5	12	12.3	32	15.3
		6,214,768	KYUSHU-A	57.7-68.3	13.5	97	13.8	94	13.3
		6,637,446	KANMONKYO	544.4-549.5	15.0	35	16.4	35	16.1

*DIRECTION is defined as Ascending (A)-towards Tokyo or Descending (D)-away from Tokyo

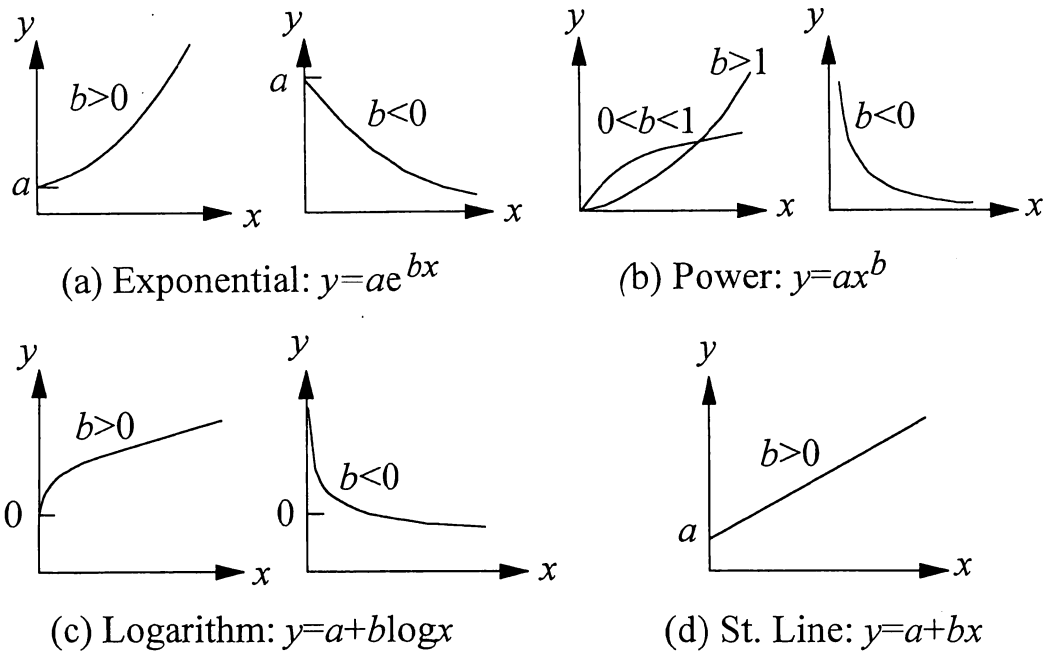


Fig. 7.1 Forms of the Four Functions for Analysis

leaving out data more than two standard deviations from the mean (see **Tables 6.1(a) & (b)**). Reduction of data to a mean value is justified because these pavements have same characteristics e. g. structure, age, traffic, etc. These rut depths were then used in the analysis which was carried within the sub-groups.

7. Trend Analysis Strategy

The selection of analysis technique was strongly influenced by data availability and the type of results required. Since the purpose was finding the effect of the factors, i. e. tracing the trend of the Rut depth vs *EAL* in the case of traffic loading and Rut depth vs pavement age in the case of environmental factor, simple functions providing different forms were used. **Fig. 7.1** shows the four functions together with their possible forms. All these possibilities were analyzed through regression analysis.

8. Analysis of Effect of Traffic Loading

8.1 Trend Analysis

Rigorous regression analysis for each of the different forms shown in **Fig. 7.1** was carried out between Rut depth and *EAL* for each structure-age group category in **Table 6. 1(a)**. Table 8.1 show coefficients of determination for each category. Among other things, the best form was selected based on R^2. From **Table 8.1**, on the overall, it is obvious that the power function provided the best form,

$$RUT = aEAL^b \tag{8.1}$$

where *RUT* is the rut depth and *EAL* is 10 ton cumulative traffic axle loads. The logarithm function which had a similar form to the power (**Fig. 7.1**) came close but the power function was the best form overall. **Table 8.2** shows detailed results of the power regression. It was noted that although a high p-value would ordinarily indicate lack of significance, it may be

Table 8.1 Rut depth vs EAL Coefficients of Determination (R^2) for Different Funtions

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

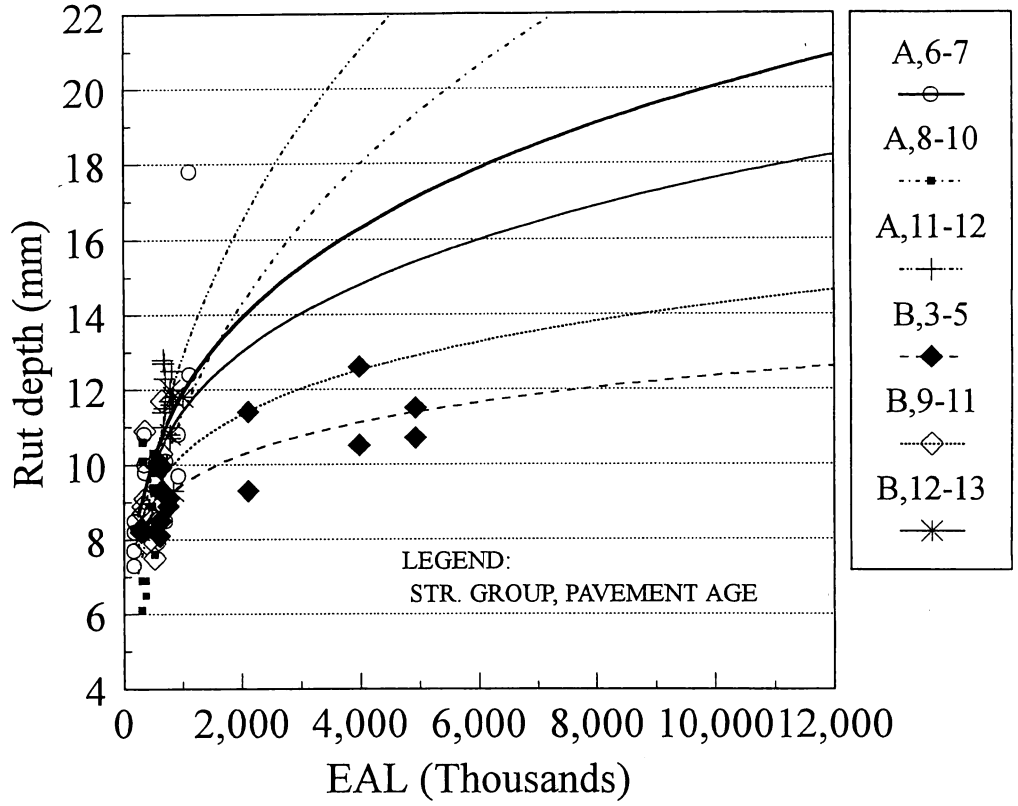
Table 8.2 RESULTS OF POWER REGRESSION OF RUTTING vs EAL ($RUT = aEAL^b$)

CATEGORY (GRP, AGE)	ESTIMATOR		p	n	R^2	Adj.R^2	SE	overall P
A, 6-7	a	0.51844	0.422	14	0.537	0.499	1.17133	0.003
	b	0.22682	0.003					
A, 8-10	a	0.1135	0.473	14	0.152	0.082	1.19859	0.168
	b	0.3334	0.168					
A, 11-12	a	0.09419	0.676	11	0.079	0	1.12308	0.403
	b	0.3559	0.403					
B, 3-5	a	1.93419	0.035	16	0.696	0.674	1.08012	0
	b	0.11508	0					
B, 9-11	a	1.42037	0.859	13	0.078	0	1.14388	0.355
	b	0.1432	0.355					
B, 12-13	a	0.85114	0.986	5	0.03	0	1.12909	0.78
	b	0.1879	0.78					
C, 5-6	a	2.05684	0.419	16	0.2	0.143	1.17222	0.082
	b	0.11288	0.082					
C, 9-12	a	1.23424	0.446	12	0.88	0.868	1.08403	0
	b	0.16615	0					
C, 15-16	a	0.40346	0.339	11	0.601	0.557	1.15667	0.005
	b	0.23761	0.005					
D, 9-10	a	0.88105	0.822	5	0.901	0.868	1.03882	0.014
	b	0.18313	0.014					
D, 11-12	a	0.23378	0.162	11	0.674	0.638	1.10538	0.002
	b	0.27173	0.002					
D, 14-15	a	0.48876	0.537	11	0.527	0.474	1.08256	0.011
	b	0.22895	0.011					

a result of a small sample size[14]. **Figs. 8.1(a)** and **(b)** show the graphs for each age category for structural groups A&B and C&D respectively.

8.2 General Equation

To further assess the effect of different factors, a general equation was developed. This was done by further expressing a and b in eq. 8.1 against structural strength and age. Representative numerical values for T_A and CBR representing structural groups (**Table 3.1**) were used. Applying stepwise regression to coefficient a and exponent b of eq. 8.1 against Age, CBR, and T_A, the following relations were obtained:



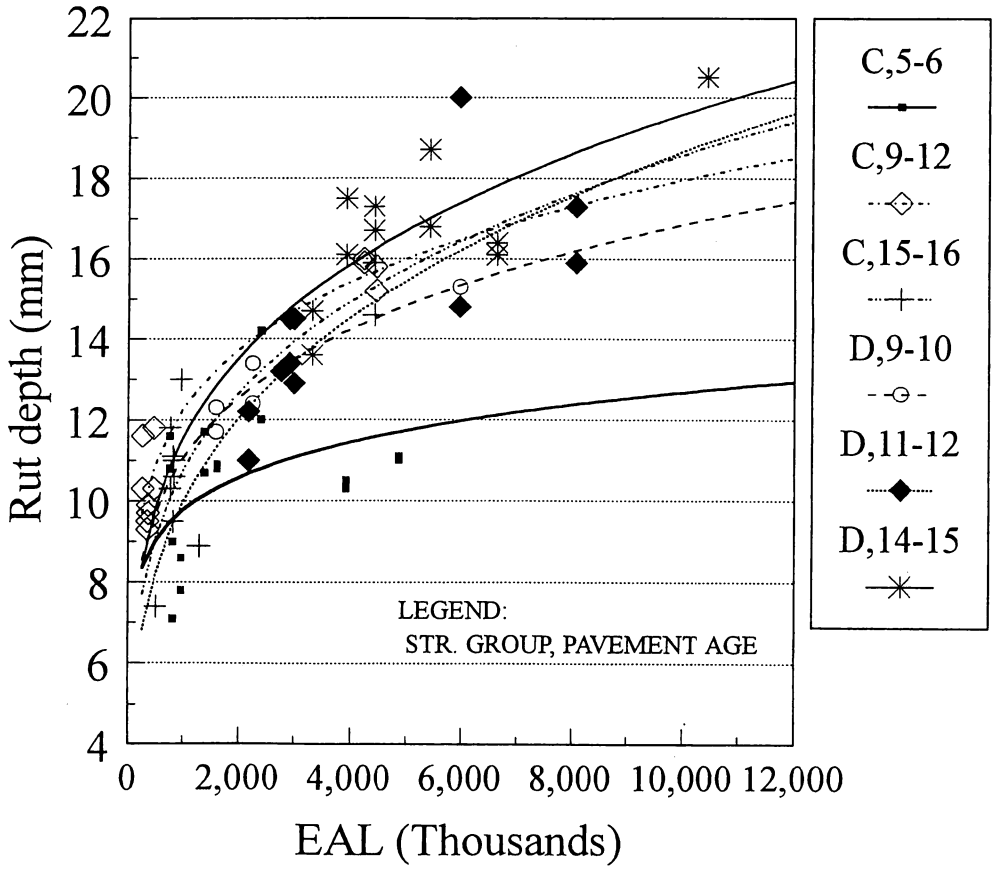


Fig. 8.1(a) & (b) Rut Depth vs EAL graphs Depicting Traffic Loading Effect

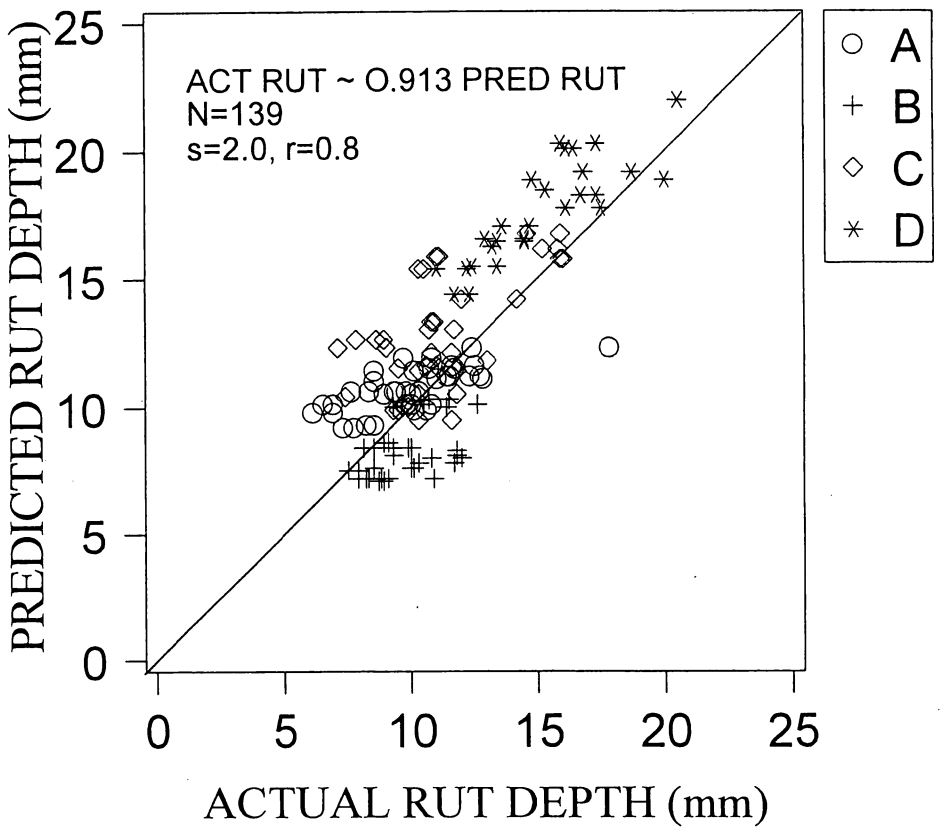


Fig. 8.2 Predicted vs Actual Rut depth (eqs. 8.1, 8.2, 8.3)

$$a = 949.1 - 946AGE^{0.001} \tag{8.2}$$

s = 0.47537, $R^2 = 0.49$

$$b = 0.119 + 0.00757AGE - 0.00000132CBR^4 \tag{8.3}$$

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

Both equations are significant at a confidence level of 0.05. **Fig. 8.2** shows rut depths predicted using the equation against actual rut depths for 139 data representing all groups of pavement structure. The equation well predicts rut depths with a standard error of about 2 mm and a correlation coefficient of r = 0.8

8.3 Discussion of the Results

Fig. 8.1 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. 6.1**). Traffic loading affects pavement rutting in a power function i. e. a lot of rutting takes place in early stages of loading and then levels off as loading increases. Also, in **Figs. 8.1**, it can be observed 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 the compaction of the newly constructed pavement layers.

As for the general equation, combining eqs. 8.1, 8.2, & 8.3, the coefficient *a* depends solely on pavement age while the exponent *b* depends on both age and *CBR* *b* increased with age and decreased with *CBR* as expected. Though further analysis shows that age has more influence on *b* compared to *CBR*, better *CBR* reduces the amount of pavement rutting to a large extent. 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. Age influence is more pronounced on pavements with high *EAL*. 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 no influence was surprising. However, all trials and rational observation proved so. This could be explained as that, in the long run, subgrade *CBR* is more important in reducing pavement rutting.

9. Analysis of Environmental Effect

9.1 Trend Analysis

Regression analysis for each of the different forms shown in **Fig. 7.1** was carried out between rut depth and pavement age for each of the pavement structure-EAL group category in **Table 6.1(b)**. **Table 9.1** shows the resulting coefficients of determination for each category. On the overall, from R^2 values, together with rational judgment, it was decided that the exponential function provided the best form,

$$RUT = ae^{bAGE} \tag{9.1}$$

where *RUT* is rut depth and *AGE* is pavement age. **Table 9.2** shows detailed results of the exponential regression. **Figs. 9.1(a)** & **(b)** show graphs for each age category for structural groups A&B, and C&D respectively.

9.2 General Equation

To model environmental effects and further detailed understanding, a general equation expressing coefficients *a* and *b* in eq. 9.1 as functions of *EAL*, T_A and *CBR* was developed. Group representative values of T_A and *CBR* in **Table 2.1** were used. Stepwise regression, with careful observation, was applied on *a* and *b* values in **Table 9.2** and the following expressions were obtained:

$$a = 8.132 + 0.00333EAL^{0.5} - 0.00024\,T_A^3 \tag{9.2}$$

$s = 0.9871$, $R^2 = 0.64$, $\text{Adj}-R^2 = 0.56$

Table 9.1 Rut depth vs Age Coefficients of Determination (R^2) for Different Funtions

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

Table 9.2 RESULTS OF EXP. REGRESSION OF RUTTING vs AGE ($RUT = ae^{bAGE}$)

CATEGORY (GRP, EAL)	ESTIMATOR		p	n	R^2	Adj. R^2	SE	overall p
A, 0.6-0.8mil.	a	5,903	0	16	0.271	0.219	1.1802	0.039
	b	0.05464	0.039					
A, 0.7-0.9mil.	a	7.2348	0	16	0.25	0.197	1.1643	0.049
	b	0.03653	0.049					
A, 0.8-1.0mil.	a	10.1158	0.001	5	0.17	0	1.1177	0.49
	b	0.01355	0.49					
B, 0.4-0.6mil.	a	7.8312	0	5	0.44	0.253	1.0926	0.222
	b	0.01883	0.222					
B, 0.5-0.7mil.	a	8.509	0	11	0.286	0.207	1.1041	0.09
	b	0.01633	0.09					
B, 0.6-0.8mil.	a	8.5336	0	10	0.719	0.684	1.0668	0
	b	0.02352	0					
C, 0.6-0.8mil.	a	6.895	0	8	0.484	0.398	1.1455	0.055
	b	0.02656	0.055					
C, 0.8-1.0mil.	a	7.06	0	10	0.765	0.736	1.1021	0
	b	0.02948	0					
C, 1.4-2.4mil.	a	8.809	0	10	0.381	0.304	1.1907	0.057
	b	0.02736	0.057					
C, 4.2-4.8mil.	a	11.4067	0	8	0.334	0.223	1.1528	0.134
	b	0.02277	0.134					
D, 1.5-3.0mil.	a	9.31	0	10	0.282	0.192	1.0746	0.114
	b	0.02808	0.114					
D, 2.0-3.5mil.	a	7.8766	0	12	0.379	0.317	1.0744	0.033
	b	0.04333	0.033					
D, 4.0-6.0mil.	a	9.1889	0	9	0.703	0.66	1.0739	0.005
	b	0.0426	0.005					
D, 5.5-6.5mil.	a	9.725	0	9	0.39	0.309	1.1144	0.072
	b	0.03418	0.072					

$$b = 0.05579 - 0.0029CBR \tag{9.3}$$

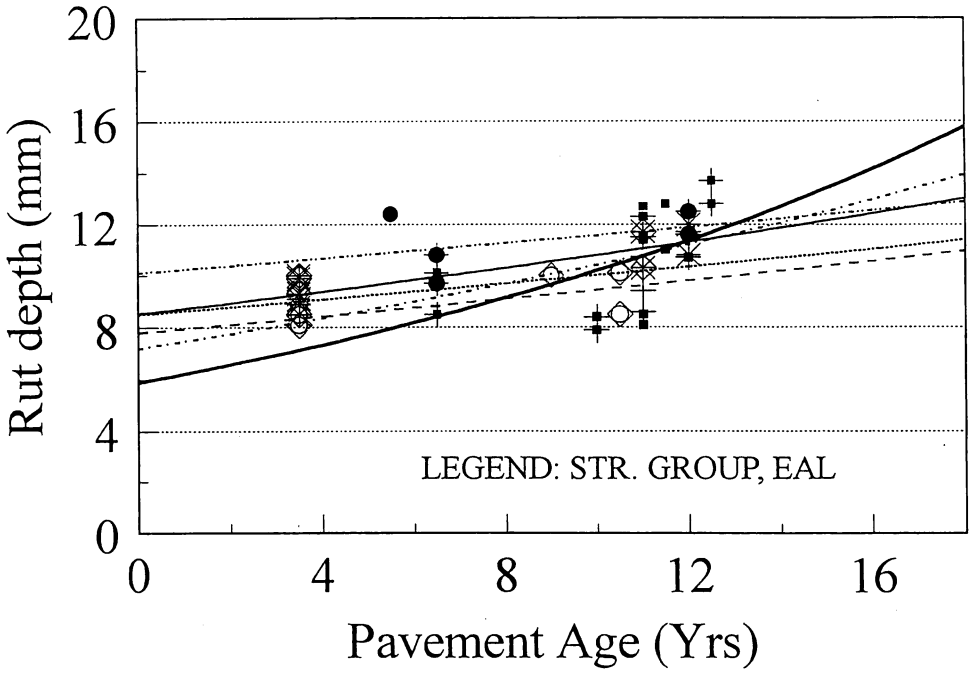
s = 0.01011, R^2 = 0.34

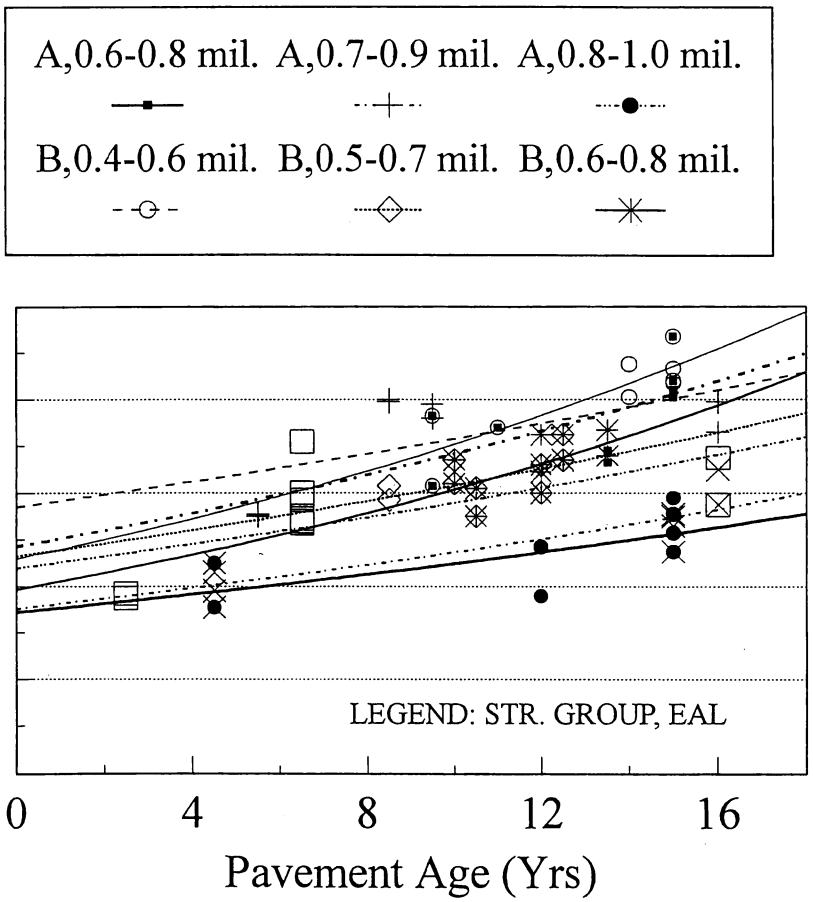
Both equations and parameters are significant at a confidence level of 0.05. **Fig. 9.2** shows rut depths predicted by the equation against actual rut depth for all groups of pavement structure. There was good agreement with a standard error of 1.75 and a correlation coefficient of 0.81.

9.3 Discussion of the Results

Figs. 9.1 depict the typical trend of environmental effect on pavement rutting i. e. environmental effects increases exponentially. It can be concluded that, under similar loading and structural conditions, rutting is severer in older pavements i. e. environmental effects become severer with age. As the pavements become older, environmental effect become severer and pavements are more vulnerable to rutting. This observation is very important in observing the progression of rutting due to environmental forces. Other than traffic loading, the different graphs show that structural strength is a factor too with weaker pavements affected more by environmental forces.

As for the general equation (eqs. 9.1, 9.2, 9.3), the coefficient a provides a coefficient to the overall rut depth equation. In tangible sense, it also represents the initial pavement rut depth at age = 0. a depends on EAL and T_A, increasing with EAL and decreasing with T_A as expected. The fact that exponential form was depicted instead of a power form, which can give the same form but starts at the origin (see **Fig. 7.1**) confirms the importance of the idea





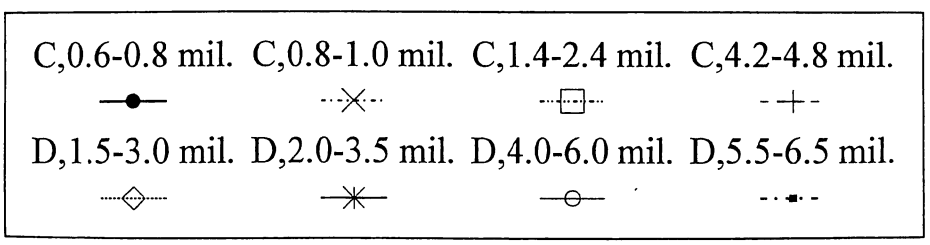


Fig. 9.1(a) & (b) Rut Depth vs Age graphs Depicting Environmental Effect

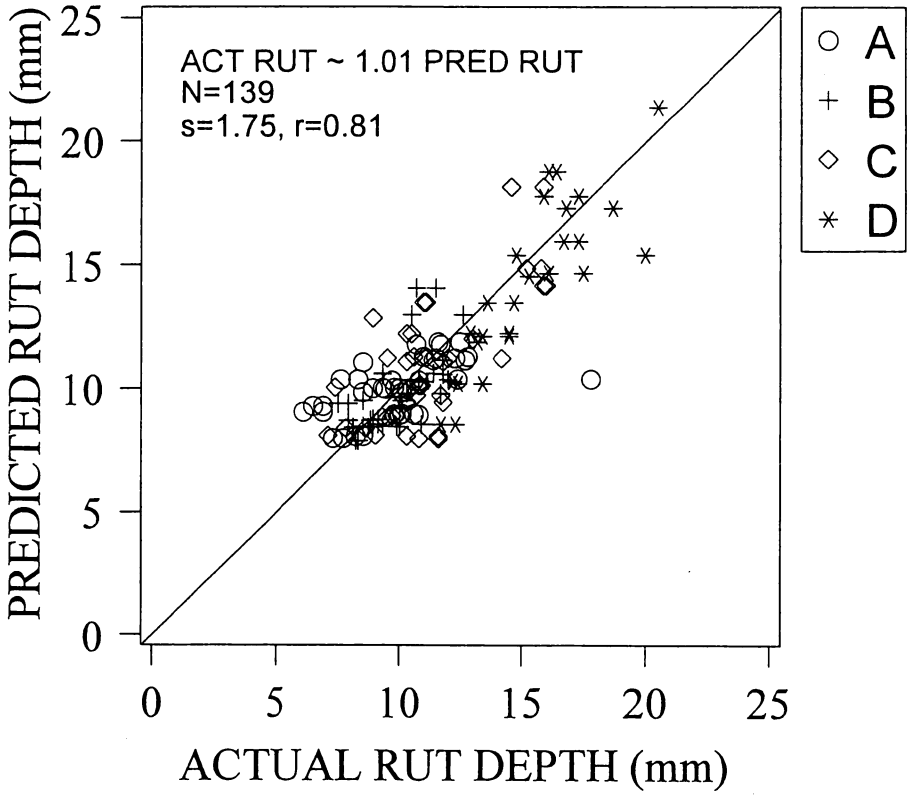


Fig. 9.2 Predicted vs Actual Rut depth (eqs. 9.1, 9.2, 9.3)

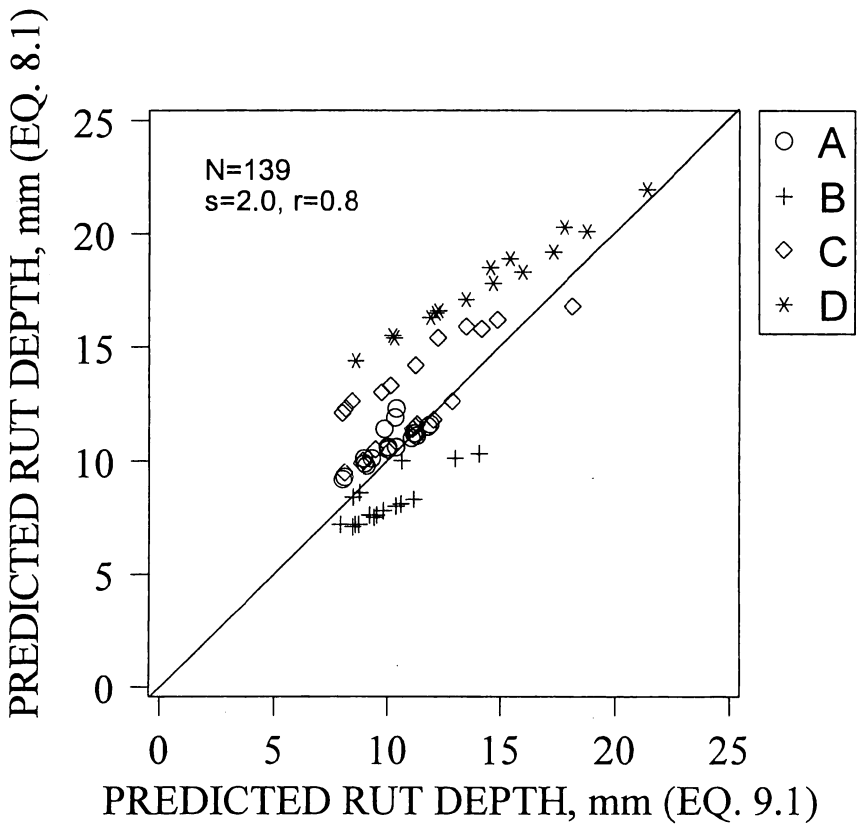


Fig. 10.1 Comparison of the two equations

of initial pavement rut depth. At zero traffic loading ($EAL=0$), the initial pavement rut depth depends solely on T_A, i. e.

$$a = 8.132 - 0.00024\,T_A^3 \tag{9.4}$$

The initial pavement rut depth is 6.2 mm for pavement of $T_A=20$ and 1.7 mm for pavements of $T_A=30$. The sole dependence of initial rut depth on T_A shows that the initial rut depth is related to pavement material, thickness, and probably construction quality as most values used were as constructed T_A values. b determines the rapidness with which rutting occurs with age since it controls the degree of curvature of the curve. The bigger the subgrade *CBR*, the less the curvature and therefore the increase in rutting. Subgrade *CBR* is therefore instrumental in reducing environmental effects on pavement rutting. For instance, using the equation, a pavement under the following conditions; $EAL=10$ mil, $T_A=25$, $AGE=10$ yrs will have 22 mm rutting if its subgrade *CBR* is 6 and 18 if it is 13.

10. Conclusions

Though two different equations were developed for the analysis of the two effects, they both predict almost same values of rut depths as shown in **Fig. 10.1**. In short, the following conclusions can be drawn:

1. Though environment affects pavement rutting, 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.
2. Traffic loading influences pavement rutting in a power function i. e. more rutting occurs in early stages of loading leveling off as more loading occurs later on.
3. Environmental effect on pavement rutting increases exponentially i. e. environmental effects on pavement rutting become severer with time.
4. Subgrade *CBR* is instrumental in reducing pavement rutting due to traffic loading in the long run, and also influences environmental effects on pavement rutting. Higher *CBR* results in less rutting.
5. The initial pavement rut depth depends on T_A i. e. pavement layers thicknesses, materials, and construction quality.

References

1) Guidelines for Pavement Management Systems. AASHTO, Washington, D. C., 1990.
2) Remaswamy, R. and Ben-Akiva, M. Estimation of Highway Pavement Deterioration from In-Service Pavement Data. Transportation Research Record 1272, TRB, National Research Council, Washington, D. C., 1990.
3) Special Report 61E: AASHO Road Test Report 5-Pavement Research. HRB, National Research Council, Washington, D. C., 1962.
4) Monismith, C. L. Analytically Based Asphalt Pavement Design and Rehabilitation: Theory to Practice, 1962-1992. Transportation Research Record 1354, TRB, National Research Council, Washington, D. C., 1992. p. 6.
5) Baladi, G. Y., Novak, E. C., Jr., and Kuo, W. H., "Pavement Condition Index-Remaining Service Life," Pavement Management Implementation, ASTM STP 1121, Frank B. Holt and Wade L. Gramling, Eds., American Society of Testing and Materials, Philadelphia, 1992. p. 73.
6) National Expressway Practices in Japan-PAVEMENT. NIHON DORO KODAN (JAPAN HIGHWAY CORPORATION), 1993.

7) AASHTO Guide for Design of Pavement Structures. AASHTO, Washington, D. C., 1993.
8) Finn, F. N., Saraf, C. L., Kulkarni, R., Nair, K., Smith, W., and Abdullah, A. Development of Pavement Structural Subsystems. Final Report NCHRP 1-10, February 1977.
9) Day, R. W. Pavement Deterionation: Case Study. Journal of Performance of Constructed Facilities, Vol. 9 No. 4. ASCE. Nov., 1995. p. 311.
10) Potter, J. F. and O'Connor, M. G. D. The TRRL Transverse Profilometer for Measuring Wheeltruck Rutting. TRRL Research Record 195. U. K. Transport and Road Research Laboratory, Crowthorne, Berkshire, England, 1989.
11) Hensley, M. J. and Leahy, R. B.. Asphalt Concrete Mixtures as Related to Pavement Rutting: Case Studies. Transportation Research Record 1217, TRB, National Research Council, Washington, D. C., 1989.
12) Design Guidelines. NIHON DORO KODAN (JAPAN HIGHWAY CORPORATION)
13) Thompson, M. R. and Nauman, D. Rutting Rate Analysis of the AASHO Road Test Flexible Pavements. Transportation Research Record 1384, TRB, National Research Council, Washington, D. C., 1993. p. 38.
14) Devore, J. L. Probability and Statistics for Engineering and the Sciences. Duxbury press, Bermont, California. 1991. 3rd ed.
15) Draper, N. R. and Smith, H. Applied Regression Analysis. Wiley Series in Probability and Mathematical Statistics. New York, Jan. 1981, 2rd ed.