

# **SHORT-TERM ROUGHNESS PROGRESSION ON NEWLY BUILT CONCRETE PAVEMENTS**

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## ABSTRACT

The smoothness or riding comfort of Portland Cement Concrete Pavement (PCCP) is an acceptable indicator of quality of construction. Smoothness specifications for newly built PCCP's in Kansas have evolved over last 15 years and have led to smoother pavements. However, some new PCCP's in Kansas have experienced rapid smoothness loss immediately after opening to traffic. This paper discusses early-life roughness progression of newly built PCCP's in Kansas. Six test sections of three newly constructed PCCP projects were selected to monitor roughness progression with time and traffic. Test sections with varying PCCP slab thickness from 280 to 320 mm on stabilized drainable bases and lime-treated subgrade were selected. As-constructed as well as periodic profile measurements (4, 8, 12, and 16 months after opening to traffic) were made by a South Dakota-type profiler. International Roughness Index (IRI) values were computed from the measured profiles. It was found that the mean IRI values with respect to single application of curing compound were significantly different from those on sections with double application. The IRI value at a particular time period after construction is significantly different from as-constructed IRI. A set of models was developed to describe the short-term roughness progression on these pavement sections. These models show that short-term IRI is a function of as-constructed IRI. Some other variables that affect short-term roughness are: thickness of concrete slab, 28-day concrete core compressive strength, 28-day stabilized base compressive strength, percent subgrade material passing 75 micron sieve, and percent entrained air in concrete. The parameter estimates of all these variables were found to be positive i.e. the short-term IRI value increases with increase in values of these variables.

Keywords: PCCP, Curling, IRI, Roughness, Profilometer

## INTRODUCTION

Smoothness of a newly constructed Portland Cement Concrete Pavement (PCCP) is now a major concern in the highway industry. It is believed that the motorists perceive a good road as one that provides a smooth ride. Studies at the road test sponsored by the American Association of State Highway Officials (AASHO, now AASHTO) showed that the subjective evaluation of a pavement, based on mean panel ratings, was primarily influenced by roughness (1). State highway agencies have recognized pavement smoothness as an important measure of pavement performance. Pavement smoothness is mostly controlled by the longitudinal profile of the road. Different wavelengths have different effects on the ride quality depending on vehicle characteristics and driving speed. Thus, smoothness is an important indicator of riding comfort and safety. Rough roads result in discomfort, reduction in speed, potential damage to vehicles, and increase in operating cost (1).

There are several factors that contribute to the pavement roughness or lack of smoothness: built-in construction irregularities, traffic loading, environmental effects, and construction materials (1). Construction irregularities can cause variations in the pavement profile from the design profile. The roughness of a pavement increases with increase in traffic loading. Environmental effects such as temperature and moisture gradient across the thickness of slab can cause curling which in turn affect the roughness of the pavement (2).

Figure 1 shows the temperature measurements in a newly constructed concrete pavement slab with variable rate of curing compound application. A high temperature differential exists between the top and bottom of this slab as evidenced by this figure. It appears that the curing technique of a newly built PCCP could affect the as-built curling and in turn, smoothness measurements on newly placed concrete pavements (3). Similar observations have also been made by FHWA (4).

Smoothness specifications for newly built PCCP's in Kansas have evolved over the last 15 years through applications and a number of revisions. The first PCCP with smoothness specifications was built by Kansas Department of Transportation (KDOT) in 1985, and the first specifications for as-constructed smoothness were adopted in 1990 (5). Changes to the original specifications of 1990 are considered to have enhanced the quality of new pavement construction in Kansas. However, early life (1 to 2 years after construction) roughness increase on some newly built concrete pavements was quite noticeable.

## OBJECTIVE

The objective of this study is to evaluate short-term roughness progression on newly built Portland Cement Concrete Pavements in Kansas and to identify the factors that affect short-term roughness.

## TEST SECTIONS

Profile data was collected on six (6) PCCP sections in Kansas built in the Summer and Fall of 2000 as shown in Table 1. All sections are jointed plain concrete pavements with 5-meter slabs

and doweled joints, and are located on Interstate routes 70 and 135. All sections have 100 mm stabilized drainable subbase, known as bound drainable base (BDB) in Kansas, and 150 mm lime-treated subgrade, as shown in Table 2. Most of the subgrade materials are fine and plastic. The effect of lime-treatment was variable as indicated by the before- and after-lime treatment plasticity index values. Subbase stabilization was done with cement and cement-fly ash binder and was drainable. A drainable base is defined as the one with a minimum of 303 m/day (1000 ft/day) permeability. The 28-day compressive strength of BDB materials was variable and ranged from 0.90 to 4.44 MPa.

Two of the I-70 sections, located near Paxico (PTS-1 and PTS-2), consist of 320 mm concrete slab while the other two on I-70 in Topeka (TTS-1 and TTS-2) have 280 mm slabs. The two test sections on I-135 in Salina (STS-1 and STS-2) have 290 mm concrete slabs. Both I-70 and I-135 are 4-lane divided highways. All test sections consist of 32 continuous slabs (i.e. 160 m long) and are located on both lanes in one direction. Figures 2 (a) and 2 (b) show the layout of Paxico and Salina test sections, respectively. The test sections on each site are adjacent to each other and were built on the same day. A single coat of curing compound was applied on the sections designated as “1” and the sections designated as “2” received two coats of curing compound. The curing compound was applied at a variable rate because of the fact that curing quality was judged to be a factor affecting the curling of slabs during construction. It is hypothesized that nonuniform temperature rise in fresh concrete and evaporation of water from the top contribute to “as-built” curling. This “as-built” curling is known to contribute to excessive roughness of PCC pavements (6). If the curing is proper, such curling could be minimized.

Two different compositions of aggregates were used in the concrete as shown in Table 2. Sixty percent fine and 40% coarse aggregates were used for concrete on the Paxico test sections. All other sections had 55% fine and 45% coarse aggregates. Concrete on all sections were air-entrained. The water-cement ratio varied from 0.45 on the Salina test section to 0.49 on the Paxico test section. The Paxico section had the highest 3-day modulus of rupture values (4.1 MPa) of concrete but the lowest 28-day core compressive strength (31.7 MPa).

## DATA COLLECTION

Data was collected in different phases of construction. Data collected can be divided into three categories: a) inventory; b) climatic; and c) profile. Inventory data includes layer and material properties data, such as, Plasticity Index (PI) of subgrade soil (before and after lime treatment), compressive strength of concrete used for the BDB layer, concrete properties, etc. as shown in Table 3. Inventory data also included road structure and geometry data as well as traffic data in terms of cumulative 80-kN (18 kip) Equivalent Single Axle Loads (ESAL). Climatic data included temperature data of pavement top and bottom during the day of construction (thermocouples were used for this purpose), mean monthly precipitation, and air temperature.

After construction, profile data was collected periodically. As-constructed data was collected 2 to 3 weeks after construction before opening the sections to traffic. After sections were opened to traffic, profile data was collected at approximately every four months. Profile measurements were done on both wheel paths of both lanes (driving and passing) using a South

Dakota-type Profiler and three replicate runs were made. The South Dakota-type profiler used in this study was an International Cybernetics Corporation (ICC) profiler with laser sensors (shown in Figure 3). All profile data was collected at about 75 mm (3 inch) intervals with the profiler operating at highway speed (80 km/hr).

## DATA ANALYSIS

International Roughness Index (IRI) was used as a summary statistic. IRI values were computed from the profile data with the RoadRuf software developed by the University of Michigan Transportation Research Institute. As-constructed IRI values for all sections are shown in Figure 4. It is to be noted that these IRI values represent the average IRI of both wheel paths and lanes with three replicate runs on each wheel path. The figure shows that the Paxico test sections had the lowest as-constructed IRI. This section had the highest water-cement ratio in the concrete mixture. The as-constructed IRI values on other sections were somewhat comparable. Table 4 and Figure 4 show that the as-constructed IRI values for sections with single application of curing compound are lower than the IRI values on sections with double application.

Table 4 and Figure 5 show the variation of IRI values with respect to time. Almost all sections exhibit definite patterns and some of the variations could be attributed to the seasonal changes. IRI values for section TTS-1 were the highest for all cases. Topeka test sections (TTS-1 & 2) have higher grade than any other sections. It is to be noted here that, 8-month data for PTS-1 and PTS-2 were not available as those sections were used as work-zone during that time period. The results also indicate that the roughness increase for the PTS sections were the lowest. The concrete on this section had the highest 3-day modulus of rupture. A previous study in Kansas has found that pavements sections with high early flexural strength tends to retain as-constructed smoothness longer (7). After 16 months, the IRI values for the sections in Topeka and Salina (TTS and STS) with double curing compound were much lower than the single curing compound sections. This may indicate that the double application of curing compound is beneficial in the long run. During field measurements, double curing compound application was found to decrease the temperature differential between the top and the bottom of the slab in fresh concrete by about 1.2 to 3.9<sup>0</sup> C compared to a single application of curing compound.

## STATISTICAL ANALYSIS

Significant factors that affect the short-term smoothness of PCCP's were found using the Analysis of Variance (ANOVA) technique and the SAS software (8). The response variable in the analysis was the measured IRI. There were four independent variables: a) Lane (driving and passing); b) Wheel path (left and right); c) Curing compound application (single and double coats); and d) Time (0, 4, 8, 12, and 16 months). Each test site was analyzed separately. The model for this experiment was:

$$IRI_{ijkl} = LANE_i + WPATH_j + CURING_k + TIME_l + \varepsilon_{ijkl} \quad (1)$$

Where,  $IRI_{ijkl}$  = International Roughness Index (m/km),

$LANE_i$  = ith Lane effect,

$WPATH_j$  = jth Wheel Path effect,

$CURING_k$  = kth Curing Compound Application effect,

$TIME_l$  = lth effect of Time of Data Collection, and

$\varepsilon_{ijkl}$  = Error term.

The results of ANOVA are shown in Table 5. All conclusions were drawn at 95% confidence level. The results show that for all sections, application of curing compound and time have significant effects on short-term smoothness. The least square mean (LSMEAN) method was used to compare the effect of time periods on IRI. The IRI values were found to vary significantly over the time periods studied. Table 5 also shows that the lane and wheel path do not have any effect on the measured IRI at the Salina and Topeka test sections.

Multiple regression analysis was used to find out the functional relationships between IRI at different time periods and significant factors that influence IRI. The general form of the model is:

$$IRI = a + bX_1 + cX_2 + \dots \quad (2)$$

where  $X_1, X_2, \dots$  are independent variables;

$a$  is the intercept; and

$b, c, \dots$  are the correlation coefficients.

Table 6 shows the list of independent variables chosen to develop the regression models. The variables include a variety of traffic, construction, and climatic factors. Models were selected based on a number of statistical information, such as,  $R^2$  value, t-test statistic, as well as engineering judgment. Several methods are available to develop such models in SAS. The backward selection model was used for this study. This method considers a full model and then evaluates reduced models (with one of the explanatory terms removed) until a reduced model is selected. In this study separate models were developed for each time period. Table 7 lists the significant independent variables, parameter coefficients and statistical information for the models obtained by SAS. The models are described below:

*Model for As-constructed IRI:* In this model, three parameters appear to be significant factors that affect as-constructed IRI values. They are: thickness of the concrete slab, 28-day core compressive strength, and 28-day compressive strength of BDB. Traffic was not considered as an independent variable since the projects were yet to be opened to traffic. As shown in Table 4, parameter estimate of all significant factors are positive, i.e. the as-constructed IRI increase with the increase in values of these factors. The  $R^2$  value of this model was found to be 0.865.

*Model for 4-month IRI:* In this model and models for 8, 12, and 16-month IRI, as-constructed IRI value was considered as one of the independent variables. For the 4-month IRI model, three variables were found to be significant: longitudinal grade, percent subgrade material passing 75-micron (US No. 200) sieve, and as-constructed IRI. The parameter estimates were all positive. The  $R^2$  value was found to be 0.857.

*Model for 8-month IRI:* Three factors were found to be significant for this model: thickness, compressive strength of BDB, and as-constructed IRI. The  $R^2$  value was found to be 0.845.

*Model for 12-month IRI:* Table 4 shows the selected model for this case. Only two variables significantly affected the 12-month IRI: percent subgrade material passing 75-micron (US No. 200) sieve, and as-constructed IRI. A high  $R^2$  value of 0.987 was obtained for this model.

*Model for 16-month IRI:* Only two variables appeared to be significant for the 16-month IRI values: percent air in concrete and as-constructed IRI value. But the  $R^2$  value obtained in this model was only 0.623, much lower than those obtained for other models.

These models show that as-constructed smoothness is highly influenced by the strength of concrete and the paving process. The model indicates that higher IRI would result from a concrete mixture whose 28-day compressive strength is higher. It is to be noted that such a mixture usually will have a lower water-cement ratio and will be somewhat difficult to handle. This assertion is further supported by the fact that thickness of the slab is also a significant factor in determining as-constructed smoothness- the higher the slab thickness, the higher is the as-constructed IRI roughness. Similar observations for long-term roughness were made by Perera and Kohn (9) in their analysis of Long Term Pavement Performance (LTPP) profile data. The strength of the bound drainable base also affects the as-constructed roughness. The model shows that higher base strength results in higher as-constructed roughness. It can be assumed that if the base is very stiff it will be somewhat “unyielding” and the profile of the base would significantly affect the as-constructed smoothness of the concrete slab. Stiffer base influences the curling of the slab. Stabilized bases are known to have pronounced effect on curling.

The short-term smoothness of Portland cement concrete pavements depends upon the as-constructed IRI value. In the short term, traffic does not have any effect on the measured IRI values. It is also interesting to note that different factors appeared to be significant at different points in time. However, thickness of the slab and percent material passing 75-micron sieve appeared in more than one model.

## CONCLUSIONS

This paper deals with the short-term roughness progression on six newly built concrete pavement sections in Kansas. The roughness was expressed in terms of International Roughness Index (IRI). Roughness data, collected periodically on these sections since construction, was statistically analyzed to find the effects of different construction, climatic and traffic factors. The Analysis of Variance (ANOVA) technique was used. The results showed that the mean IRI values with respect to single application of curing compound were significantly different from those on the sections with double application of curing compound. IRI value at a particular time period (for example, 4 months after construction) was significantly different from other time period (e.g. as-constructed IRI). A set of models was developed to describe the short-term roughness progression on these pavement sections. These models show that short-term IRI is a function of as-constructed IRI. Some other variables that affect the short-term roughness are: thickness of concrete slab, 28-day concrete core compressive strength, 28-day stabilized base compressive strength, percent subgrade material passing 75 micron sieve, and percent entrained

air in concrete. The parameter estimates of all of these variables were found to be positive i.e. the short-term IRI value increases with the increased values of these variables.

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## REFERENCES

1. Hass, R., W. R. Hudson, and J. Zaniweski. *Modern Pavement Management*. Krieger Publishing Company, Florida, 1994.
2. Ytterberg, R. F. Shrinkage and Curling of Slabs on Grades: Part II – Warping and Curling. *Concrete International*, Vol. 9 No. 5, May 1987, pp. 54-61.
3. Siddique, Z. Q., M. Hossain, J. Devore, and W. J. Parcels, Jr. Effect of Curling on As-Constructed Smoothness of Portland Cement Concrete Pavements. Published on TRB CD-ROM, Paper No. 02-3142, Washington D.C., January 2002.
4. FHWA. *Midwestern Pavement News*. Issue 2000-01, Federal Highway Administration Midwest Resource Center, Olympia Fields, Illinois, May 2000.
5. Parcels, Jr., W. H. and M. Hossain. Kansas Experience with Smoothness Specifications for Concrete Pavements. *In Transportation Research Record 1435*, TRB, National Research Council, Washington D.C., 1994.
6. Byrum, C.R. Analysis of LTPP JCP Slab Curvature Using High Speed Profiles. *In Transportation Research Record 1730*, Transportation Research Board, National Research Council, Washington D.C., January 2000.
7. Akhter, M., Hossain, M., Boyer, J., and Parcels, W. Factors Affecting Roughness Progression on PCC Pavements in Kansas. *Forthcoming in the Transportation Research Record*, Journal of the Transportation Research Board, National Research Council. Washington D.C., January 2002.
8. SAS, Statistical Analysis System, The SAS Institute, Carey, North Carolina, 1979.
9. Perera, R. W. and S. D. Kohn. LTPP Data Analysis: Factors Affecting Pavement Smoothness. *NCHRP Project 20-15[8/13]*, Web Document 40, TRB, National Research Council, Washington D. C., August 2001.

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**TABLE 1 Details of Test Sections**

Test Section Name	Section Symbol	Route	Station		Grade (%)
			Begin	End	
Paxico 1	PTS-1	I-70	27+200	27+037.5	0.0
Paxico 2	PTS-2	I-70	23+712.5	23+550	0.4
Salina 1	STS-1	I-135	25+850	26+012.5	0.1
Salina 2	STS-2	I-135	25+462.5	25+625	0.1
Topeka 1	TTS-1	I-70	346+25	351+50	4.0
Topeka 2	TTS-2	I-70	339+70	344+95	4.0

**TABLE 2 Concrete Mix Design Properties**

Section	% Aggregate in Mix		% Air	Water-Cement Ratio	Cement Content (kg/m <sup>3</sup> )	28-day Core Compressive Strength (MPa)	3-day Modulus of Rupture (MPa)
	Coarse	Fine					
PTS-1	40	60	6.5	0.49	330	31.7	4.10
PTS-2	40	60	6.5	0.49	330	31.7	4.10
STS-1	45	55	7.0	0.45	325	44.5	3.30
STS-2	45	55	7.0	0.45	325	44.5	3.30
TTS-1	45	55	7.5	0.47	335	41.4	3.92
TTS-2	45	55	7.5	0.47	335	41.4	3.92

**TABLE 3 Subgrade and Base Material Properties**

Section	Plasticity Index (%)			Subgrade Material Passing 75-micron Sieve (%)	BDB Compressive Strength (MPa)
	Before Lime Treatment	After Lime Treatment	Change		
PTS-1	22.5	20.0	2.5	96	0.90
PTS-2	20.5	18.5	2.0	96	N/A
STS-1	20.0	N/A	-	90	1.93
STS-2	23.0	N/A	-	90	2.24
TTS-1	26.5	19.5	7.0	97	4.44
TTS-2	20.0	21.5	0.5	97	4.11

**TABLE 4 Mean IRI Values for Different Sections with Respect to Time**

Time	Test Section	Mean IRI (m/km) Value			
		Curing Application			
		Single		Double	
		DL <sup>#</sup>	PL <sup>+</sup>	DL	PL
As-Constructed	Paxico	1.00	1.03	0.99	1.11
	Salina	1.33	1.33	1.42	1.44
	Topeka	1.44	1.21	1.58	1.74
4-Month	Paxico	0.85	0.83	0.99	1.21
	Salina	1.14	1.18	1.18	1.04
	Topeka	1.48	1.55	1.26	1.08
8-Month	Paxico*	-	-	-	-
	Salina	1.58	1.63	1.4	1.43
	Topeka	2.2	2.45	1.87	1.87
12-Month	Paxico	1.1	1.01	1.41	1.27
	Salina	1.53	1.51	1.45	1.39
	Topeka	1.72	1.55	1.64	1.55
16-Month	Paxico	1.12	0.99	1.35	1.19
	Salina	1.46	1.47	1.36	1.24
	Topeka	1.79	2.08	1.51	1.46

# Driving Lane

+ Passing Lane

\* This section was used as work-zone during the time of data collection

**TABLE 5 Effect of Different Factors on IRI**

Test Section	Effect of Factors on Mean IRI Values			
	Lane	Wheel Path	Curing Application	Time
Paxico	Different	Different	Different	Different
Salina	Equal	Equal	Different	Different
Topeka	Equal	Equal	Different	Different

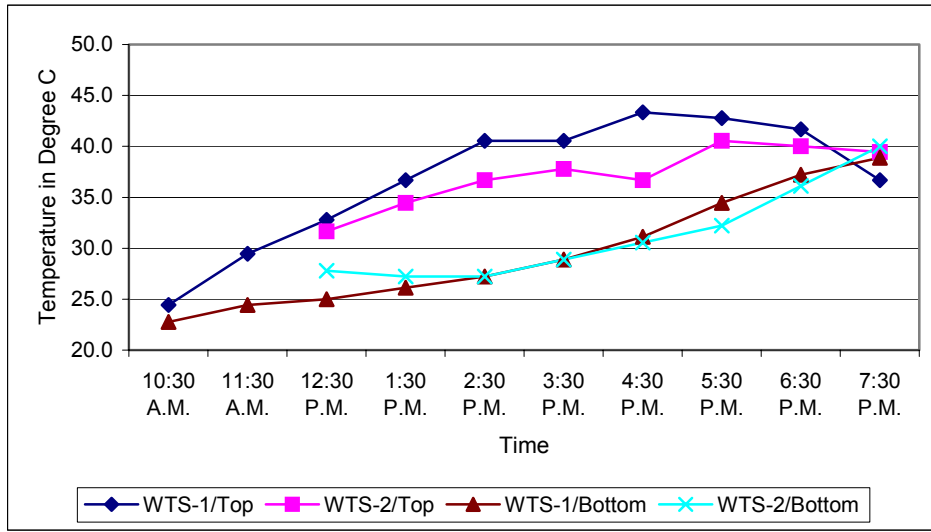
\* At 95% confidence level.

**TABLE 6 Variables Used in Models**

Traffic Data	Construction Data	Road Structure and Geometry	Climatic Data
Cumulative Equivalent Single Axle Load (ESAL)	Percent Coarse and Fine Aggregate Water-Cement Ratio Percent Air Concrete Unit Weight 28-day Core Compressive Strength Concrete Modulus of Rupture Compressive Strength of Bound Drainable Base, Change in Plasticity Index (before and after lime treatment)	Pavement Thickness Grade	Temperature Differential of Slab Top and Bottom, Mean Monthly Precipitation, Air Temperature

**TABLE 7 Models Derived for the Study**

Variable	Description	Parameter Estimate	Model Statistics
<i>As-Constructed IRI Model</i>			
Intercept	Constant	-1.79	$R^2= 0.865$ SSE=0.79
THICK	Thickness of slab (mm)	0.0054	
CSTR	28-day Core Compressive Strength (MPa)	0.0366	
BDBSR	Compressive Strength of BDB (MPa)	0.0739	
<i>4-Month IRI Model</i>			
Intercept	Constant	-0.773	$R^2= 0.857$ SSE=0.65
Grade	Grade (%)	0.012	
PASS200	% Subgrade Material Passing 75-micron (#200) Sieve (%)	0.0098	
IIRI	As-constructed IRI (m/km)	0.813	
<i>8-Month IRI Model</i>			
Intercept	Constant	-1.065	$R^2= 0.845$ SSE=0.99
THICK	Thickness of slab (mm)	0.0028	
BDBSR	Compressive Strength of BDB (MPa)	0.2562	
IIRI	As-constructed IRI (m/km)	0.755	
<i>12-Month IRI Model</i>			
Intercept	Constant	-0.788	$R^2= 0.987$ SSE=0.002
PASS200	% Subgrade Material Passing 75-micron (#200) Sieve	0.0085	
IIRI	As-constructed IRI (m/km)	0.975	
<i>16-Month IRI Model</i>			
Intercept	Constant	-1.561	$R^2= 0.623$ SSE=2.78
AIR	Percent Entrained Air in Concrete	0.2967	
IIRI	As-constructed IRI (m/km)	0.644	



**FIGURE 1 Temperature Variation of Freshly Placed Pavement Slab for Section WTS (3)**

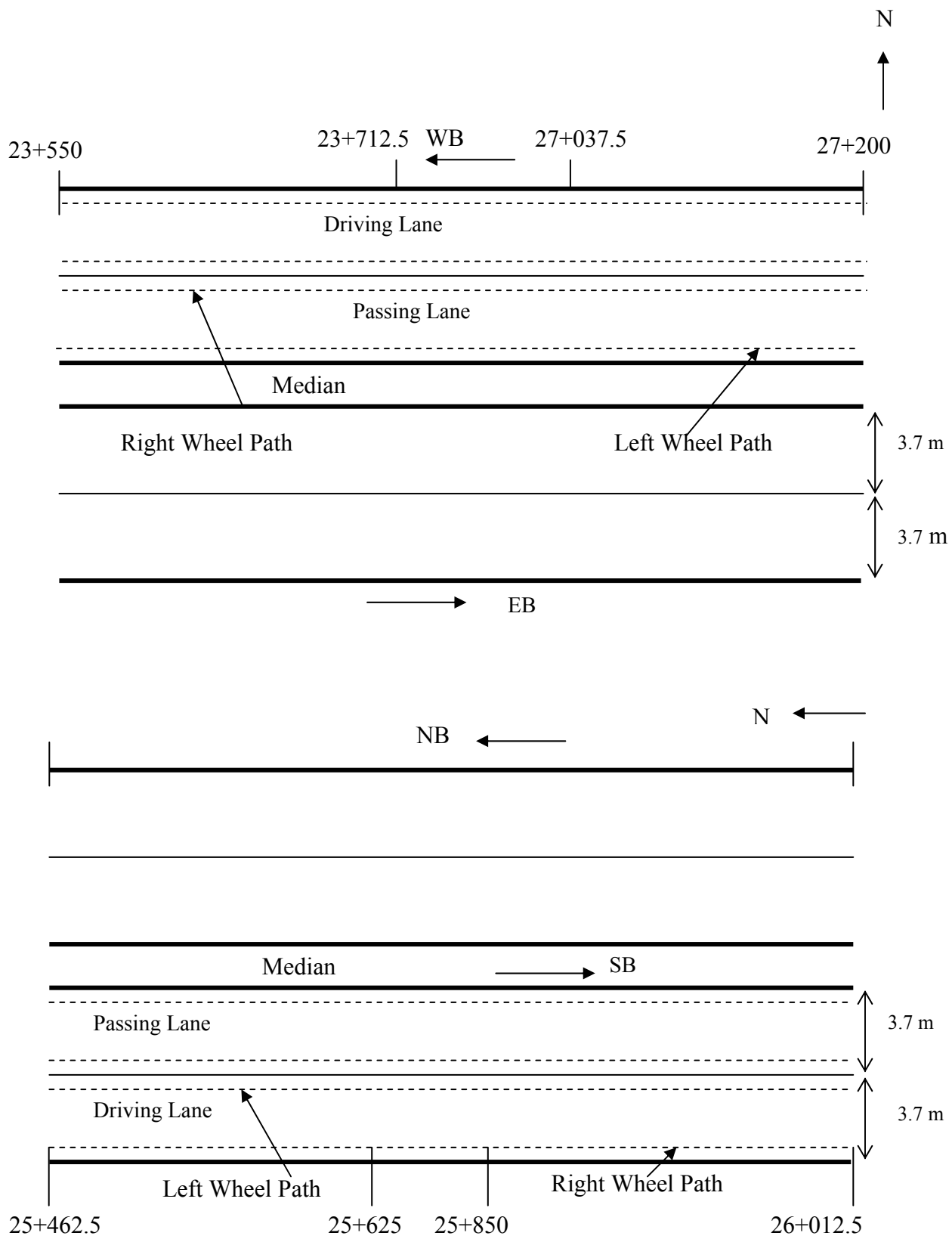
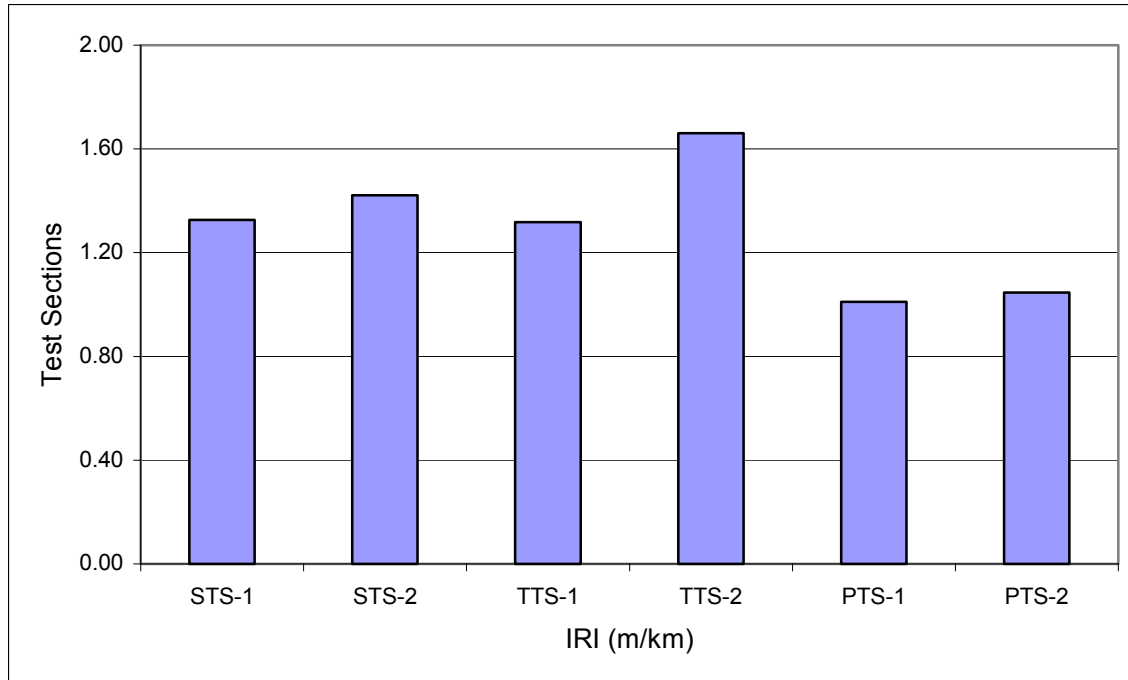


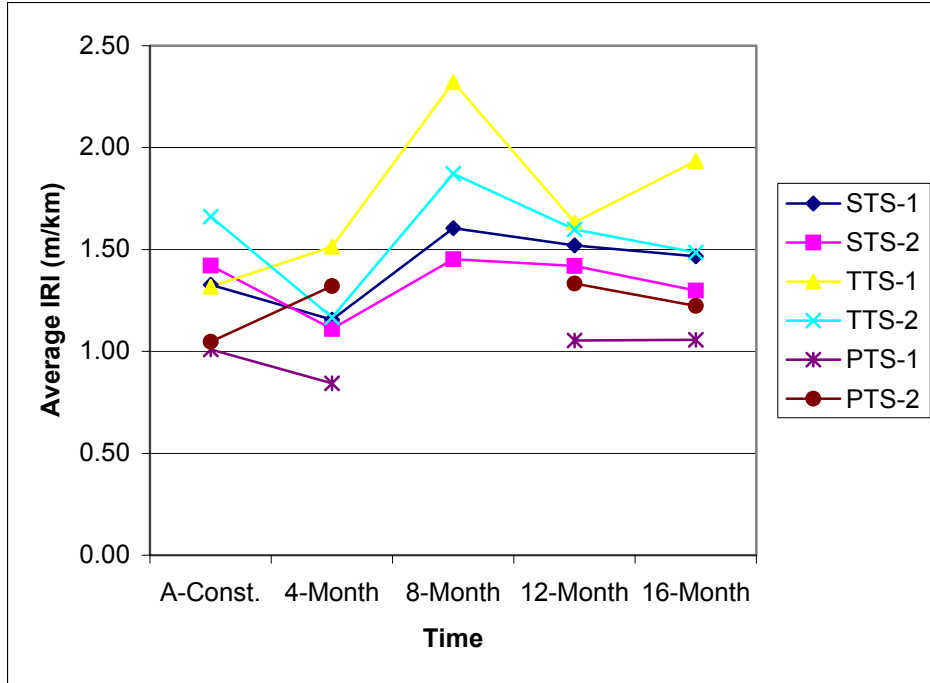
FIGURE 2 Layout of Test Sections



**FIGURE 3** KDOT South Dakota Profiler



**FIGURE 4 As-constructed IRI values for Different Test Sections**



**FIGURE 5** Variation of IRI with respect to Time