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Design Factors Affecting the Initial Roughness of Asphalt Pavements

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Abstract: Past studies have shown that initial pavement roughness greatly affects future pavement roughness and roughness progression rate. Highway agencies typically use incentives/disincentives to control the initial roughness of pavements. However, the current blanket specifications do not account for inherent factors that affect initial roughness, such as design factors. In other words, pavements are designed to have different initial roughness. This study analyzes the design factors affecting the initial roughness of asphalt-surfaced pavements. An initial international roughness index (IRI) of 442 asphalt-surfaced pavements constructed from 2000 to 2004 was analyzed based on analysis of covariates. The factors considered in this study include hot mix asphalt (HMA) layer thickness, project location (urban vs. rural), base type, HMA mix classification, and pavement length. The statistically significant factors affecting initial pavement roughness were identified and discussed. These factors can be taken into account to develop specifications for initial roughness of asphalt pavements.

***Key words**: Base type, HMA mix classification, HMA thickness, Project location.*

Introduction

According to a Federal Highway Administration survey in 2002, the public rated pavement roughness as the single most important factor affecting ride quality [1]. Pavement roughness directly affects driver comfort, fuel efficiency, safety, and vehicle depreciation. Therefore, to improve the driving conditions of the highway system, pavement roughness should be addressed with priority. Numerous studies have shown that initial pavement roughness greatly affects future roughness and roughness progression [2, 3]. In a National Cooperative Highway Research Program (NCHRP) project study, Smith et al. studied the effects of initial pavement roughness on future roughness [2]. They found that pavements that were built smooth typically stay smooth over time. Wen et al. studied the roughness progression of in service asphalt overlays on concrete pavement and reported that the initial international roughness index (IRI) was highly correlated with the current IRI [3].

It is often believed that the difference in initial roughness is due to the quality of construction by contractors/crews. The initial roughness of pavement is controlled by the highway agencies that use incentives/disincentives. However, inherent factors that affect initial roughness, such as design factors, are not included in the current blanket specifications. In other words, pavements are designed such that the initial roughness is different. Therefore, there is a need to identify the significant design factors to develop specifications for the initial roughness of new pavements. In addition, considering the importance of initial pavement roughness, it is imperative to study the factors affecting the initial pavement roughness so that measures can be taken to improve initial pavement roughness at the design stage.

Perera et al. studied the effects of design, material, and construction on asphalt pavement roughness [4]. They found that the early-age roughness of new asphalt pavements decreased with the increase of HMA layer thickness. For the asphalt overlay of existing asphalt pavement, the IRI of overlay did not depend on the IRI of existing pavement, overlay thickness, milling, or the type of HMA mix. In addition, using LTPP GPS-1 data, Perera et al. developed prediction models of the initial roughness of asphalt pavements, which take climate zones into account. According to these prediction models, the initial roughness of asphalt pavement is a function of pavement structural capacity, pavement material properties, and climate [5].

This paper presents the results of the statistical analysis of factors affecting the initial roughness of asphalt-surfaced pavements in Wisconsin. The use of local data is more instrumental in developing specifications for a highway agency than the use of LTPP data. The Wisconsin Department of Transportation (WisDOT) collected the data on the as-constructed pavements in its highway system. The effects of design factors on the initial pavement roughness were studied, including the location of pavement, HMA layer thickness, HMA classification, project length, and base type. Only the routine data collected by WisDOT were included in this study. However, a statistically significant factor will remain significant when more factors are added in the analysis.

Data Collection

The initial IRIs of the 442 newly constructed asphalt-surfaced pavements between 2000 to 2004 were collected. WisDOT measured the IRIs using a video profiler PSI-24LG in the left wheel path of the as-constructed pavements. These pavements were built by different contractors in Wisconsin. The time of measurement ranged from within one week to three months after construction. The variables, which could have significant effects on the initial IRIs, were also obtained from WisDOT's databases. These variables include HMA thickness, project length, project location, base type, and HMA mix classification. These projects consisted of reconstruction and rehabilitation. For those reconstruction projects,

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Table 1. Between-Subjects Factors.

Variable Type	Variable	Values	No. of Projects
Categorical	Classification	Pre_Superpave	143
		SuperPave	249
		SMA	6
		Warranty	44
	BASE	CABC	97
		OGBC2	16
		Existing_AC	172
		Pulverize	65
		Repo_AC_Base	8
		Existing_PCC	63
		Rubblize	21
	Location	Rural	339
		Urban	103
Continuous	Thickness	19.1 to 215.0 mm	442
	Length	0.83 to 117 km	442

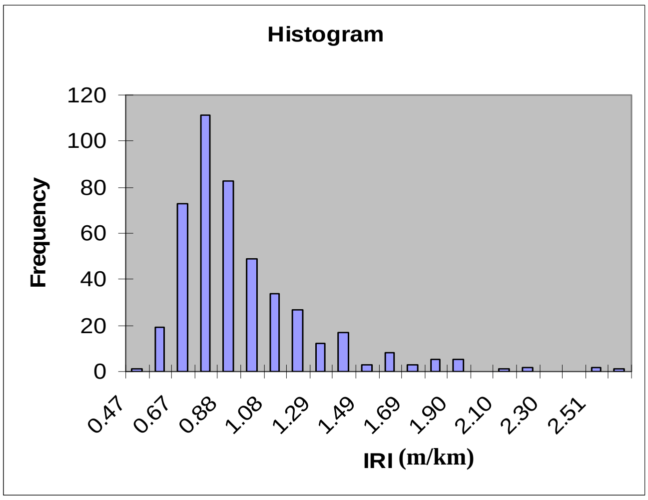

Fig. 1. Histogram of IRI.

the HMA layers were built on dense-graded crushed aggregate base course (CABC), open-graded base course (OGBC2), or reprocessed asphaltic-concrete base course (Repo_AC_Base). Repo_AC_base utilizes removed asphaltic concrete after processing in a plant. For the rehabilitation projects, the existing pavements consisted of both asphalt and concrete pavements. The existing asphalt pavements were milled partial-depth or pulverized full-depth. The existing concrete pavements were intact or rubblized. The HMA mixes used in these projects were designed using Pre_Superpave, Superpave, or stone mastic asphalt (SMA). Some of the projects were built with warranty. The HMA layer thickness ranged from 19.1 mm to 215.9 mm, and the lengths from 0.83 km to 117 km. The breakdown of the projects used in this study is shown in Table 1. Currently, the WisDOT specifications on IRI without penalty to contractors depend on the category of pavements [6]. For HMA pavements, which have multiple opportunities to achieve the acceptance levels such as multiple lifts or milling existing HMA, the acceptance level is 0.947 m/km. Pavements that have only a singular opportunity have an acceptance level of 1.34 m/km. The threshold for corrective action is 2.05 m/km.

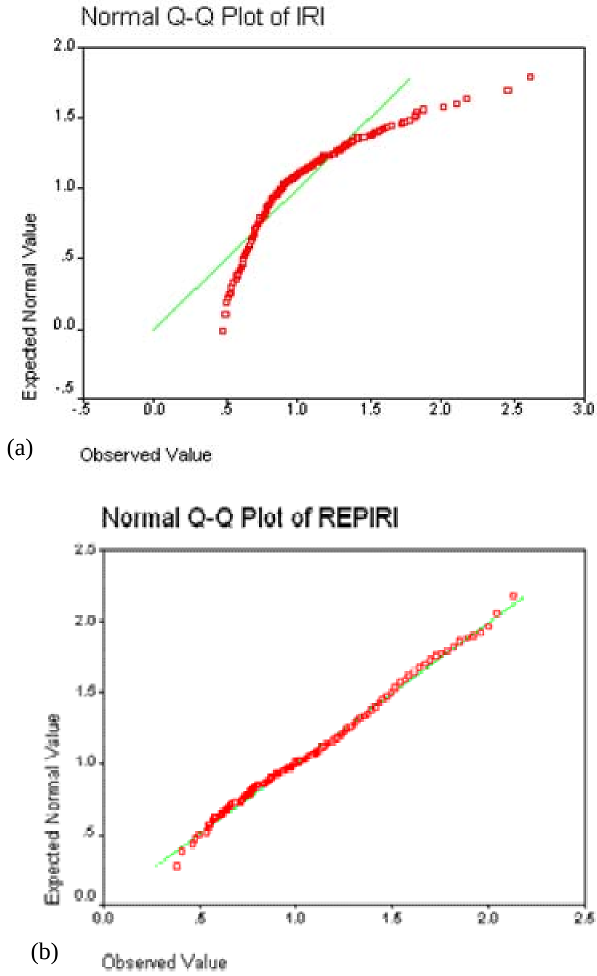

Fig. 2. (a) Q-Q Plot Before Transformation and (b) Q-Q Plot After Transformation.

Data Analysis

This study analyzes the initial roughness of 442 as-constructed asphalt-surfaced pavements. A statistical analysis was conducted to identify the factors affecting the initial pavement roughness using the analysis of co-variance (ANCOVA) in SPSS statistical package. In the statistical analysis, IRI is the dependent variable. The independent variables consist of two types of data— continuous and categorical. HMA layer thickness and project length are continuous variables. Base type, HMA classification, and project location are categorical variables. Fig. 1 shows the histogram of IRIs in this study.

One assumption using the analysis of covariate is the normal distribution of independent variable (IRI in this case). Fig. 2(a) is the quantile-quantile (Q-Q) plot of IRI (m/km). For a normal distribution, the line of Q-Q plot has to overlap with the line of linearity. It can be seen in Fig. 2(a) that the Q-Q plot deviates from the line of linearity and thus violates the assumption of normal distribution. A transformation of dependent variables is typically used to meet the requirements for normal distribution. To meet this standard, a few transformation techniques, such as square, natural logarithm, root square, and reciprocation, were used. It was found that a reciprocating transformation, 1/IRI, was able to solve

Table 2. Levene's Test of Equality of Error Variances.
Dependent Variable: 1/IRI

F value	Degree of Freedom 1	Degree of Freedom 2	Sig.
1.229	35	406	0.179

*Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

Table 3. Tests of Between-Subjects Effects.
Dependent Variable**:** 1/IRI

Source	Type III Sum of Squares	Degree of Freedom	Mean Square	F Value	Significance
Corrected Model	19.100(b)	12	1.592	26.652	0
Intercept	8.587	1	8.587	143.78	0
CLASSIFI	1.084	3	0.361	6.053	0
BASE	1.541	6	0.257	4.302	0
LOCATION	6.95	1	6.95	116.377	0
LENGTH	0.638	1	0.638	10.684	0.001
THICKNESS	0.65	1	0.65	10.881	0.001
Error	25.62	429	0.06		
Total	713.838	442			
Corrected Total	44.72	441			

a Computed using alpha = .05
b R Squared = 0.427 (Adjusted R Squared = 0.411)

the problem of non-linearity. The transformed IRI met the requirement, as shown in Fig. 2(b).

Another requirement is to use the general linear models, such as ANCOVA or analysis of variance (ANOVA) and is the equality of error variance (homoscedasticity). The equality of error variance is shown in Table 2, indicating that the requirement of homoscedasticity was met.

A 5 percent significance level was used in this study. A full model was built to test the interactions between the independent variables. The full model included all the main factors and their two-way interactions. The full model was statistically significant ($p < 0.001$). None of the interactions was statistically significant. The regression model was refined by excluding all insignificant interactions of main factors. The regression analysis results for the refined model are shown in Table 3. Table 4 presents the regression coefficient for each factor, and the dependent variable is 1/IRI, instead of IRI.

The statistical analysis indicates that all the independent variables are statistically significant, as shown in Table 3. The Bonferroni method was used to conduct multiple comparisons between the levels for each factor.

HMA Layer Thickness

The HMA thicknesses in this study range from 19.05 mm to 215.9 mm. As shown in Table 3, multiple regression results indicate that HMA thickness significantly affects initial roughness, with a p value of 0.001. The regression coefficient for pavement thickness in Table 3 is 0.04. It indicates that an increase of HMA layer thickness corresponds to an increase of 1/IRI, resulting in a decrease of the initial roughness of asphalt pavement. This finding agrees with that by Perera et al. that thicker HMA layer thickness causes lower roughness [4]. Thick HMA layer generally warrants more than one lift, which reduces the effects of base unevenness on the initial roughness of HMA surface.

Urban vs. Rural Pavement

Among the 442 as-constructed pavements, 339 pavements are located in rural areas and 103 in urban areas. Table 3 shows that the variable of project location is a statistically significant factor, with a p value of 0.000. The parameter coefficient for Rural in Table 4 is 0.356, indicating that rural pavements have a higher value of 1/IRI and thus lower initial IRI than urban pavements. Table 5 presents the mean of 1/IRI and the 95% confidence levels. Utilities are frequently encountered during urban construction. The transition into the crown of intersecting roads, as well as drainage consideration at the intersection, also affects the initial roughness. These features greatly increase the initial pavement roughness. Rural pavement construction generally has fewer interruptions, resulting in a smoother surface. The box plot in Fig. 3 clearly shows the difference of 1/IRI between rural and urban pavements.

HMA Mix Classification

The HMA mixes used in these projects were designed using the Marshall method (Pre_Superpave), Superpave method, or SMA. Some of the mixes were designated as warranty type. Among these projects, 249 pavements used Superpave mixes, 143 Pre_Superpave mixes, 44 Warranty mixes, and only 6 SMA mixes.

Results show that HMA mix classification is a significant factor, indicating that at least one HMA classification is significantly different from other classifications. As shown in Table 4, the SMA mix is a statistically significant factor with a coefficient of -0.463, while Pre_Superpave, Superpave, and Warranty are not statistically significant factors. The negative regression coefficient for SMA mix indicates that pavement with SMA had lower 1/IRI and higher initial IRI. The mean of 1/IRI and 95% confidence intervals are shown in Table 6. The statistical analysis indicates that pavement that uses SMA mixes had statistically higher initial IRI than other pavements. This can be due to the texture of SMA mixes, which affects the profiler's readings. When compared to conventional mixes, such as dense-graded HMA, SMA has a higher coarse aggregate content that interlocks to form a stone skeleton. The difference in gradation between SMA and conventional mixes can be seen in Fig. 4 [7].

There is no statistically significant difference in initial IRI between Superpave, Pre_Superpave, and Warrant pavements. This may be due to the fact that for Warranty projects roughness is not covered in the warranty items. Warranty is generally specified in terms of pavement distresses instead. Fig. 5 shows the box plot of different classifications.

Base Type

Table 4. Parameter Estimates.
Dependent Variable: 1/IRI

Parameter	Regression Coefficient	Std. Error	t value	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
Intercept	0.818	0.095	8.615	0	0.631	1.005
[CLASSIFI=Pre_Superpave]	-0.079	0.043	-1.833	0.067	-0.164	0.006
[CLASSIFI=SMA]	-0.463	0.109	-4.233	0	-0.679	-0.248
[CLASSIFI=SuperPave]	-0.078	0.042	-1.874	0.062	-0.16	0.004
[CLASSIFI=Warranty]	0(b)	.	.	.	.	.
[BASE=CABC]	-0.055	0.06	-0.918	0.359	-0.173	0.063
[BASE=Existing_AC]	0.062	0.06	1.022	0.307	-0.057	0.18
[BASE=Existing_PCC]	-0.051	0.065	-0.788	0.431	-0.179	0.076
[BASE=OGBC2]	-0.237	0.083	-2.858	0.004	-0.4	-0.074
[BASE=Pulverize]	0.017	0.062	0.271	0.787	-0.106	0.139
[BASE=Repo_AC_Base]	-0.189	0.103	-1.838	0.067	-0.391	0.013
[BASE=Rubblize]	0(b)	.	.	.	.	.
[LOCATION=R]	0.356	0.033	10.788	0	0.291	0.421
[LOCATION=U]	0(b)	.	.	.	.	.
LENGTH	0.005	0.001	3.269	0.001	0.002	0.007
THICKNESS	0.04	0.012	3.299	0.001	0.016	0.064

a Computed using alpha = .05
b This parameter is set to zero because it is redundant.

Table 5. Mean of 1/IRI and 95% Confidence Level of Rural and Urban Projects.
Dependent Variable: 1/IRI

Location	Mean of 1/IRI	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Rural	1.174(a)	0.033	1.109	1.24
Urban	.818(a)	0.04	0.738	0.897

a Covariates appearing in the model are evaluated at the following values: LENGTH = 12.2886 km, Thickness = 4.03 cm.

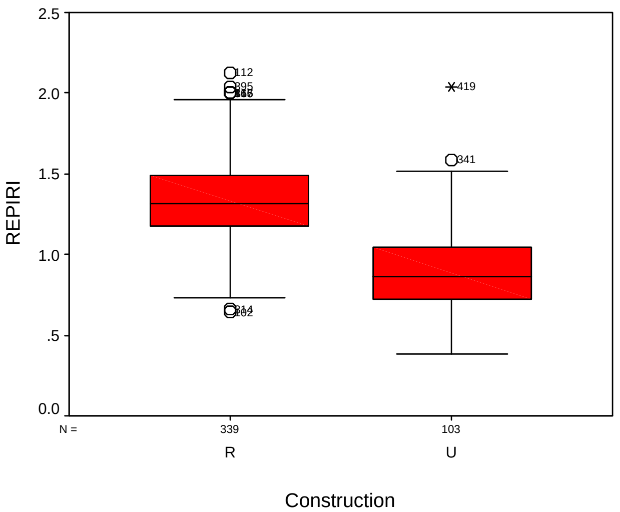

Fig. 3. Box Plot of Reciprocal of IRIs in Rural and Urban Areas.

Seven types of bases underneath the new HMA layer were used in these studies. For new asphalt pavements, the bases consisted of crushed aggregate base course (CABC), open-graded base course,

Table 6. Mean of 1/IRI and 95% Confidence Level of IRIs for Different Pavement Classification.
Dependent Variable: 1/IRI

Classification	Mean of 1/IRI	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
Pre_Superpave	1.072(a)	0.028	1.016	1.128
SMA	0.688(a)	0.103	0.485	0.89
SuperPave	1.073(a)	0.022	1.029	1.117
Warranty	1.151(a)	0.043	1.066	1.236

a Covariates appearing in the model are evaluated at the following values: LENGTH = 12.2886 km, Thickness = 4.03 cm.

Fig. 4. Texture of SMA (Left) and Conventional Mix (Right) (after [6]).

open-graded base course #2 (OGBC2), and Repo_AC_Base. Repo_AC_Base is composed of re-processed asphalt pavement materials transported from plants. Of the 90 reconstruction projects in this study, 52 pavements used CABC, 17 used OGBC, and 21 used OGBC2. CABC is dense-graded while OGBC and OGBC2 are permeable base course materials and contain much less fine materials than CABC. With more fine aggregates, CABC has better

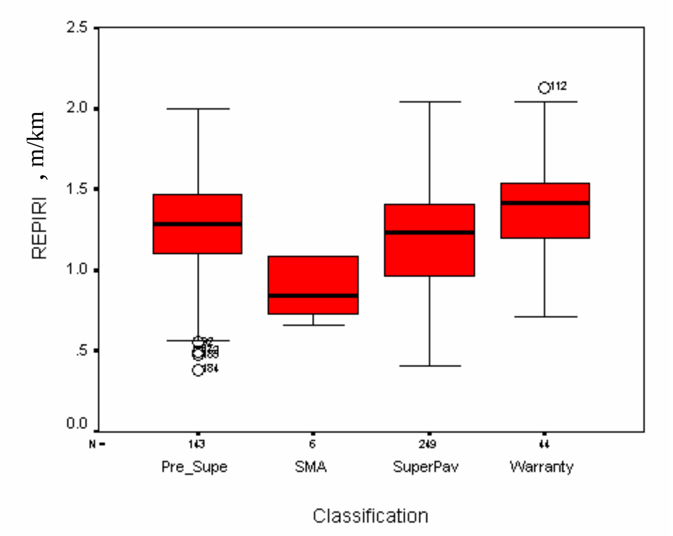

Fig. 5. Box Plot of Reciprocal of IRIs for Different HMA Classifications.

workability for the final grading of base course than OGBC and OGBC2. For asphalt overlay on existing asphalt pavement, the existing asphalt pavements were milled partial-depth or pulverized full-depth. For asphalt overlay on concrete pavements, the existing concrete pavement were intact or rubblized. Table 7 shows the mean of 1/IRI for different bases and their confidence intervals.

According to Table 7, the statistical analysis results indicate that OGBC2 caused statistically rougher pavements than other types of bases. This is probably due to the gradation of OGBC2 materials, which have less fine aggregates and relatively lower workability.

Pavement Length

The statistical analysis indicates that pavement length is a statistically significant factor, with a p value of 0.001. Fig. 6 shows the relationship between IRI and length. With the increase of pavement length, the initial roughness decreases.

Conclusions

Specifications on the initial roughness of pavement need to account for the design factors. This study was performed to identify significant design factors affecting initial roughness. The initial pavement roughness of 442 asphalt-surfaced pavements constructed from 2000 to 2004 in Wisconsin were statistically analyzed. The factors considered in this study include HMA layer thickness, HMA classification, project location, base type, and pavement length. It was found that:

(1) Thicker HMA layer shows lower initial roughness,

(2) Urban projects have a higher initial roughness than rural projects, probably due to utilities in urban pavements and/or geometric consideration for intersecting road and drainage.

(3) Asphalt surface built with SMA has a higher initial roughness than pavement with Superpave, Pre-superpave, and Warranty. This is likely due to the rough texture of SMA mixes, which can affect the profiler readings.

(4) Asphalt pavements on OGBC2 base have a higher initial roughness than pavement on other types of bases.

(5) Longer projects tend to have lower initial roughness.

Table 7. Mean of 1/IRI and 95% Confidence Level of IRIs for Different Bases.

Dependent Variable: 1/IRI

BASE	Mean of 1/IRI	Std. Error	95% Confidence Interval	
			Lower Bound	Upper Bound
CABC	1.006(a)	0.038	0.93	1.081
Existing_AC	1.123(a)	0.035	1.053	1.192
Existing_PCC	1.010(a)	0.039	0.932	1.087
OGBC2	0.824(a)	0.073	0.681	0.966
Pulverize	1.078(a)	0.042	0.995	1.16
Repo_AC_Base	0.872(a)	0.092	0.692	1.052
Rubblize	1.061(a)	0.062	0.94	1.182

a Covariates appearing in the model are evaluated at the following values: LENGTH = 12.2886, Thickness = 4.03.

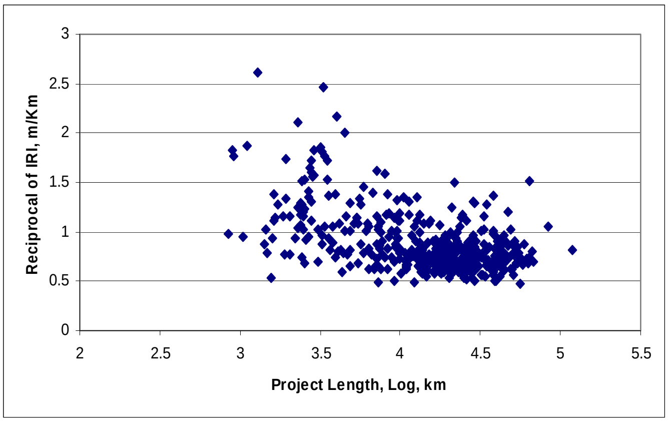

Fig. 6. Relationship between Project Length and Reciprocal of IRIs.

Based on the above observation, the initial IRIs of asphalt surface are affected by design factors. These design factors should be taken into account to develop specifications for initial roughness of pavements.

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