Survival Analysis for Composite Pavement Performance in Iowa

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(Text =4760 words, 10 Tables & Figures = 2500 words, Total = 7260 words)

Submitted to TRB conference on August 1st, 2013

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ABSTRACT

This study investigates the performance of composite pavements composed of a flexible layer over a rigid base. Four composite pavement rehabilitation methods are involved in the research: mill and fill, structural overlay, rubblization and heater scarification. Survival analysis is used to evaluate the four methods by three pavement performance indicators: reflective cracking, International Roughness Index (IRI), and Pavement Condition Index (PCI). It is found that rubblization can significantly retard reflective cracking development in composite pavements compared with the other three methods. No significant difference for PCI is seen in the survival analysis for the four rehabilitation methods. Heater scarification shows the lowest survival probability for both reflective cracking and IRI.

Further, parametric survival models are employed to analyze the influence factors on the reflective cracking for the four composite pavement rehabilitation methods. Traffic level is found not to be a significant factor for reflective cracking development. Overlay and removal thickness can significantly delay the propagation of reflective cracking and the soil type can influence the use of rubblization in the field. However, modifying the rubblization pattern may compensate for a weak subgrade.

BACKGROUND

Composite pavements comprise a large portion of the paved highway surfaces in the State of Iowa and throughout the U.S. Midwest. They are mostly the result of concrete pavement rehabilitation. The traditional pavement design approach in Iowa has been to construct thick full-depth Portland cement concrete (PCC) pavements. When they begin to fail years later they are overlaid with 2-6 inches of hot-mix of asphalt (HMA). Composite pavements, compared to traditional flexible or rigid pavements, can be a more cost-effective alternative because they may provide better levels of performance, both structurally and functionally.

A composite pavement structure, throughout its service life, may develop different types of distresses. Several research studies (1, 2) have reported that reflective cracking is the most common distress type in composite pavements. When HMA overlays are placed over jointed or severely cracked PCC or HMA pavements, they crack rapidly through the HMA overlay thickness and reflect to the surface causing reflective cracks. Although reflective cracking does not generally reduce the structural capacity of a pavement, subsequent ingress of moisture and the effects of the natural environment and traffic can result in premature distress and early failure of the pavement. The basic mechanisms leading to the occurrence of reflective cracks are horizontal and differential vertical movements between the original pavement and HMA overlay. Commonly attributed factors that cause movements at joints and cracks in the base pavement are low temperature (freeze-thaw cycles), wheel loading, temperature aging of the HMA near the surface, and the shrinkage of the concrete pavement. Among these factors, temperature-induced cracking is considered to be the critical one. The propagation rate of reflective cracks is dependent on a number of factors including the thickness of the overlay, HMA overlay properties, type of reinforcement (if used), and the subgrade condition (1). Unlike other types of pavement distress, Von Quintus et al. (1) also noticed that the growth rate of reflective cracking was very high during the early pavement service life, after which, it would be much lower.

Four widely used rehabilitation strategies for composite pavements are evaluated in this study. These include:

- HMA structural overlay,
- HMA mill & fill,
- Heater scarification (SCR), and
- PCC rubblization

The HMA overlay treatment has good performance on flexible pavement, but its applicability for composite pavements would depend on the extent of the reflective cracking. Surface recycling has been reported by Federal Highway Admiration (FHWA) to be successful in removing reflective cracks when used prior to an HMA overlay (3). Mill & fill and SCR are two common ways to remove cracks from old HMA overlays. In the SCR method, the removed pavement materials are used along with recycling agent in the re-paving process, and in the mill & fill process, the contractors typically use new asphalt concrete mix for repaving. Rubblization is defined as “breaking the existing concrete pavement slabs into smaller fragments and overlaying with HMA.” The rubblized concrete pavement has the potential to eliminate reflective cracking in HMA overlays by minimizing the concrete thermal expansion and contraction.

Two good data sources to monitor the pavement performance and reflective cracking condition after these pavement rehabilitation strategies are the Iowa pavement management system (PMS) and the Iowa Pavement Management Program (IPMP). The Iowa PMS database contains most of the primary road information (Interstate, National and State highways), while the IPMP database covers about 3500 miles of county roads and urban streets in Iowa. Both databases include continuous testing that provides 100% coverage length of the network and roadway surface (not a sample section). Data are comparable with each other in the two databases, since they follow the same method for pavement performance survey, which is defined in the “Distress Identification Manual for the Long-Term Pavement Performance (LTPP) Project (5). The literature has shown that reflective cracking can be rated in the same manner as transverse cracking for composite pavements (2, 4). In this study, only transverse cracks are considered as reflective cracks for each test section in the PMS and IPMP databases and any transverse length crack counts as one crack in the analysis.

SURVIVAL ANALYSIS

In order to track the growth rate of reflective cracking and composite pavement performance in an amount of time for each type of rehabilitation method, survival analysis, or more generally, time-to-event analysis is used. The term survival analysis s(t) is used predominately in biomedical sciences where the interest is in observing time to death either of patients or of laboratory animals. The engineering sciences have also contributed to the development of survival analysis where it is called "reliability analysis" or "failure time analysis". Using the reliability analysis, Bausano, et al. (6) compared the reliability of four different types of HMA pavement maintenance treatments using the Michigan PMS database. Dong and Huang (7) employed the survival function to evaluate four types of HMA pavement cracks using the LTPP database. The survival analysis focusing on the hazard function was applied by Yang (8) to estimate the duration of pavement life in Florida. Survival data are generally described and modeled in terms of two related functions, namely survival and hazard. The survival function s(t) and hazard function h(t) are inter-related (see Eq.1). If either s(t) or h(t) is known, the other can be determined. Consequently, either can be the basis of statistical analysis (9). S(t) measures the survival probability beyond some time t, while h(t) measures the failure probability occurring in the next instant, given survival to time t.

$$h(t) = -\frac{d}{dt}\left[\log s(t)\right] \qquad \text{Eq.(1)}$$

In this study, three pavement performance indicators are applied, and include reflective cracking, International Roughness Index (IRI), and Pavement Condition Index (PCI), with the emphasis on reflective cracking. From the point of statistics, the specific difference related to survival analysis arises largely from the fact that survival data should be divided into censored and uncensored groups. Censoring is when an observation is incomplete due to some random cause. In the area of pavement performance, censored data (loss to follow up) occurs if a pavement project performs well during the observation life, while uncensored data (failure) is obtained when a pavement project is distressed beyond the performance indicators' threshold values during the observation period.

THRESHOLD VALUE

The threshold values are used to determine the censored and uncensored data. The threshold values are the lowest acceptable pavement condition level before pavement preservation treatments become necessary. A lower threshold value is used for local/county roads, for they usually have much lower traffic and longer service lives. Although there seems to be no universal threshold values for the pavement maintenance or rehabilitation treatment, the IRI and PCI values shown in Table 1 are generally for pavements in fair or poor condition (10). The range and description for each performance index are also provided. To quantify the severity and extent of reflective cracking, a simple reflective crack index (RCI) is developed. The formula is also shown in Table 1. The index is based upon the extent of reflective cracking and the weight function of the crack severity to account for the condition of reflective cracking. Taking three levels of crack severity into consideration, the RCI can reflect out a more real distress condition than merely evaluate only one facet of the cracking, such as the total reflective crack length or amount of cracks per kilometer or mile. In Figure 1, a typical ascending trend for RCI can be observed. The RCI value is represented by the shaded area based on the right axis. Reflective crack numbers for low severity level, on the left axis, develop quickly at the beginning, and start to decrease later as more cracks move into medium and high severity levels. In other words, the RCI can not only reflect out the changes of total crack number, it can also show the influence of severity condition. The threshold value for RCI is set to be 500 for primary roads. Based upon the threshold value, at least 500 low severity, 167 medium severity, or 84 high severity cracks are allowed per kilometer to trigger the threshold. This threshold could be slightly higher than what is recommended by other highway agencies that the total length of reflective cracking should be less than 1000 ft./mile or the whole numbers of reflective cracking should be no more than 251 (11, 12).

TABLE 1 Summary of Three Performance Indicators

Pavement Condition Index	Range	Trigger	Description
Reflective crack index (RCI)	0 to inf.	RCI ≤ 500 (primary road) RCI ≤ 450 (county road)	$RCI = Low \times 1 + Med \times 3 + High \times 6$; Low, Med., High: represent numbers of low, medium and high severity reflective crack per km.
International Roughness Index (IRI)	(0 to inf.) in./mi	125 in/mi (primary road) 120 in/mi (county road)	Irregularities in the pavement surface. The higher value, the rougher road surface would be.
Pavement Condition Index (PCI)	0 to 100	64 (primary road) 68 (county road)	Composite index including cracking, ride quality & rutting. The lower value, the poorer road condition would be.

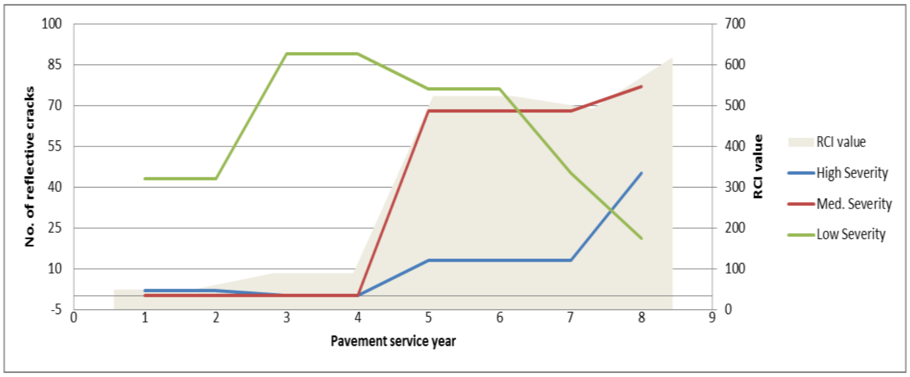


FIGURE 1 A Typical Relationship for Reflective Cracking and RCI in Double Axis (IA-12 highway, STP-12-1(16)—2C-97)

OBJECTIVES

The main objective of this study is to identify the most appropriate pavement rehabilitation method for composite pavement and to evaluate the influence of different factors for the reflective crack development in composite pavement by survival analysis.

DATA PREPARATION

This study utilizes pavement performance, traffic and pavement structural data from the Iowa PMS and IPMP databases. Pavements constructed from 1998 through 2007 are chosen for this research. The performance for these projects was tracked until the latest 2012 pavement performance survey. Totally, 158 projects are collected. These include 42 projects for mill and fill treatment, 54 HMA overlay projects, 32 projects for heater scarification and 31 rubblization projects. The JMP life distribution and survival platform is used for the data analysis (13).

DISCUSSION OF RESULTS

Kaplan-Meier Estimator

In any statistical analysis, it is always a good idea to perform univariate analysis before proceeding to more complicated models. In survival analysis it is highly recommended to look at the Kaplan-Meier curves for all the categorical predictors. This will provide insight into the shape of the survival function for each group and give an idea of whether or not the groups are proportional. The Kaplan-Meier estimator is a nonparametric maximum likelihood estimator of survival function. It incorporates information from all of the observations available, both uncensored and censored, by considering survival function to any point in time as a series of steps defined by the observed and censored times (9). Figure 2 compares the graph of Kaplan-Meier estimate for the four different rehabilitation methods on reflective cracking. The largest time length is 14 years as shown in the figure, and this is the maximum survival time from 1998 to 2012. As can be seen, the survival function decreases as the pavement age increases as expected. The survival function for the rubblization treatment lies completely above the other three treatments and it has a long right tail with relatively constant survival function. The survival function for the overlay and SCR groups cross three times in between 5 to 10 years, suggesting that the survival experience for the two groups may be similar in the time range. A typical pattern for all the three treatments (SCR, overlay and mill & fill) is: relatively early rapid descending survivor function with a gradually longer tail in the later service life. This is the result of a number of early failure and a few projects with survival near the maximum follow-up time. Table 2 summarizes the median survival time, as well as other percentiles, which are determined by linear interpolation. The median value or 50th survival percentile is always considered as the service life that a pavement can sustain before failure (14). The test statistics are further examined whether or not the four types of treatments are significantly different in the survival function for reflective cracking. Log-rank and Wilcoxon tests are the two simple comparison methods provided in JMP software. In general, the Log-rank test places more emphasis on the differences in the curves at larger survival time values, while the Wilcoxon test places more weight on early survival time values. The results show that the rubblization treatment can significantly reduce the occurrence of reflective cracking compared to the other three treatment methods, which is the cause of the high probability of test separation in the Log-Rank and Wilcoxon test analysis for the reflective cracking.

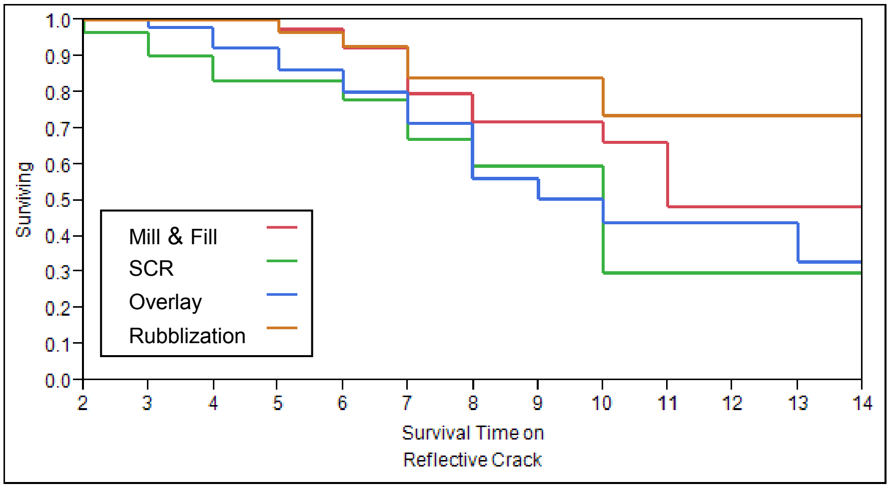
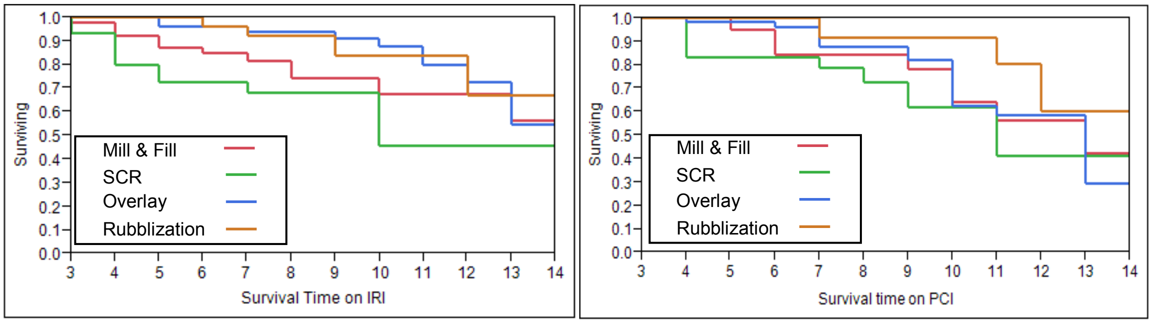


FIGURE 2 Kaplan-Meier Estimator Curves for Reflective Cracking

TABLE 2 Percentile Summaries and Test between Groups for Reflective Cracking

Group	Number failed	Number censored	70% Percentile	Median	30% Percentile
Fill & Mill	14	28	8.1	10.8	N/A
Hot in-place	12	20	6.6	9.0	9.89
Overlay	27	27	7.1	9.0	N/A
Rubblization	5	26	N/A	N/A	N/A
Combined	58	100	7.5	10.2	N/A
Test	**ChiSquare**	**DF**	**Prob>Chisq**		
Log-Rank	7.90	3	0.0482*		
Wilcoxon	8.25	3	0.0411*		



(a) (b)

FIGURE 3 Kaplan-Meier Estimator Curves for IRI (a) and PCI (b)

TABLE 3 Tests between Groups for IRI and PCI

Test between groups for IRI			Test between groups for PCI	
Test	Prob>Chisq		Test	Prob>Chisq
Log-Rank	0.0215*		Log-Rank	0.215
Wilcoxon	0.0027*		Wilcoxon	0.082

Figure 3 illustrates the relationship of survival function and pavement service life based on IRI and PCI. It is noticed that the roughness (IRI) survival function for each treatment method falls within a relatively narrow band. Mill & fill, overlay and rubblization treatments are all effective in keeping the pavement smooth within the 14 years of life. However, the SCR treatment using the recycled asphalt concrete does have a significantly higher pavement roughness in the service life as shown in Figure 3. Table 3 shows that there is no significant difference among the survival curves for PCI. As a composite index measuring the comprehensive pavement condition, the survival function of PCI may indicate that although certain methods can improve the reflective cracking condition, they may also induce other distresses such as rutting, longitudinal cracking, etc. Finally, these lead to similar pavement service lives on PCI for the four rehabilitation methods.

Model Fitting

The Kaplan-Meier estimator is used for describing the survival experience of a population, which does not require any specific distributional assumptions about the shape of the survival function. At this point, the parametric model for survival analysis is considered, which may provide us more information on the relationship between variables and the survival function. Several parametric models are commonly used; these include Exponential, Weibull, Lognormal and Logitsic models. The most obvious distinguishing feature between the models is in the shape of the hazard function they assume the data follow. The Weibull distribution model is appropriate when the hazard is always increasing or decreasing; In the Exponential model, the hazard is assumed to be constant over time. Hazard function of the Logistic model follows an "S-curve" behavior. The Log-Normal model is preferable when the hazard rises to a peak before decreasing.

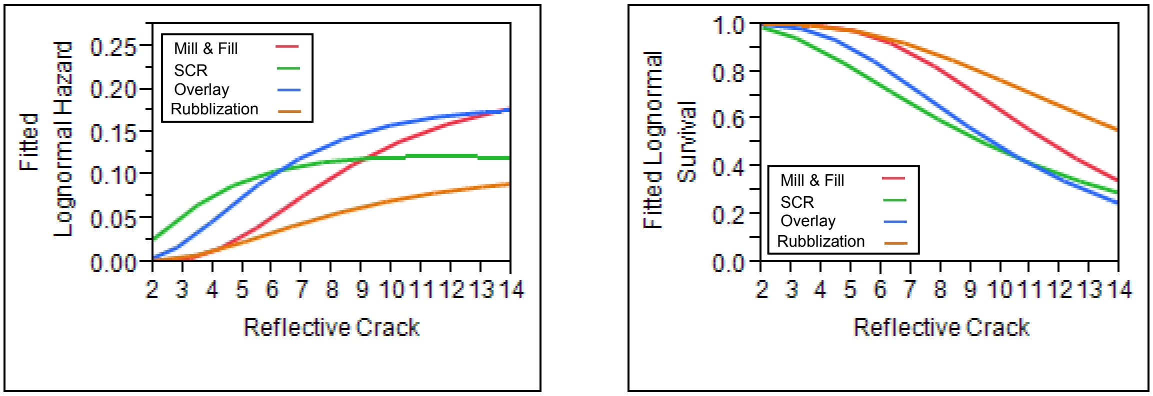
There are a few diagnostic methods available for model selection and comparison. Ideally, the selected model should reflect physical pavement cracking & performance development patterns. In this study, Akaike's information criterion (AIC) is applied, since it works for both univariate and multivariable survival analysis. AIC as suggested by Akaike (15), is an estimate of the relative distance between the unknown true likelihood function of the data and the fitted likelihood function of the model. A lower AIC value means a model is considered to be closer to the truth. In a general case, the method to estimate the AIC value is shown in Eq. 2, where L is the maximum likelihood function, k is the number of parameters of the chosen survival model.

$$\text{Minimize } AIC = 2k\text{-}2\ln(L) \qquad \text{Eq.(2)}$$

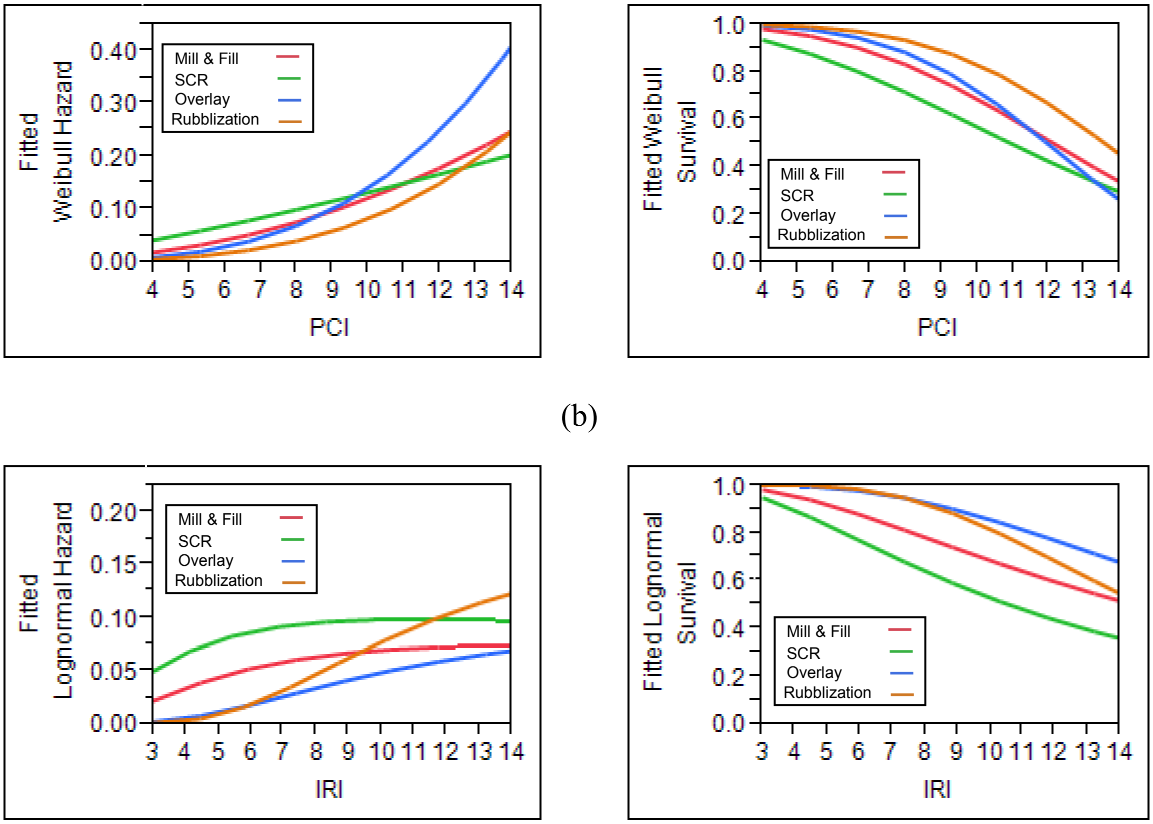
TABLE 4 Model Comparisons by the AIC Values

AIC value	Lognormal	Weibull	Logistic	Exponetial
Reflective Crack	425.677	427.906	438.238	494.199
PCI	302.067	300.543	304.866	357.766
IRI	293.95	295.56	304.92	314.82

For the univariate analysis performed here, there are three parameters (pavement service life, intercept and error part). As shown in Table 4, the Lognormal distribution appears to be the best-suited for modeling the general trend of reflective cracking and IRI, while the Weibull model is the best fit for PCI. Further, the modeled hazard function and survival function are presented in Figure 4 for the three pavement condition indicators. The hazard function sometimes can give clearer information about the underlying mechanism of failure than the survival function. Figure 4(a) shows that there is early reflective cracking failure risk for SCR and overlay methods, followed by a constant hazard in the later stages of pavement life. The mill & fill has a steep rising curve in later service life. The hazard rate for rubblization treatment, on the other hand, gradually increases during the natural failure process. Although showing different patterns in the hazard rate, the survival function for the PCI is close to that observed for reflective cracking as shown in the parametric curve in Figure 4(b). The hazard and survival function for the IRI seems not to follow the trend of reflective cracking. An obvious higher hazard rate is noticed in the early life for SCR. This could be attributed to the initial IRI condition (condition of a pavement at the time of treatment application). Unlike pavement distress data (no cracks initially), the roughness-based initial IRI values vary greatly from 75 in/mile to 110 in/mile. Subgrade condition, roadway speed requirement, asphalt concrete mix type, construction quality, etc. all can affect the initial IRI value.



(a)



(b)

(c)

FIGURE 4 Summary for the Model Fitted Hazard and Survival Functions for Reflective Cracking (a), PCI (b), IRI (c)

Multivariate Survival Analysis

In the field, various factors/covariates can influence the performance of the pavements. The relationship between reflective cracking and these factors are evaluated here. In addition to the pavement performance, traffic, pavement thickness and pre-treatment condition in the PMS database are also collected. Pre-treatment condition refers to the old IRI value before the rehabilitation treatment. Only average daily traffic (ADT) information is recorded in the database and it is used to represent the general traffic level for each project. Multivariable survival analysis using parametric survival models is established for the four pavement rehabilitation methods. Table 5 presents the best-fitted parametric models for each treatment method via the Akaike's information criterion. The selected models could be different from those used in the univariate analysis due to the effects of the new added covariates. The likelihood ratio test results in Table 5 check the significance of each covariate by comparing the log-likelihood from the fitted model. The significance level is 0.05 for this test, and corresponds to a 95% level of confidence. Figure 5 displays the failure function profiler for the four rehabilitation methods. The failure function/probability is one minus the survival function. This profiler can be used to show the failure probability as one of the covariates is changed while the others are held constant by dragging the red dot line. Observations from the Figure 5 are discussed as follow.

TABLE 5 Summaries of AIC Test and Likelihood Ratio Test Results

Method	Fit model	Influence factors	likelihood ratio test	
			L-R ChiSquare	Prob>Chisq
Mill &Fill	Weibull	HMA thickness	9.117	0.0025*
		Removal thickness	7.082	0.0078*
		ADT	0.396	0.5659
HIR	Lognormal	HMA thickness	15.999	<.0001*
		Removal thickness	1.1547	0.2826
		ADT	0.2859	0.5928
Overlay	Lognormal	HMA thickness	5.173	0.0229*
		Pre-condition	0.008	0.9294
		ADT	0.590	0.4423
Rubblization	Lognormal	Soil type	3.017	0.0824

Mill & Fill

According to the likelihood ratio tests in Table 5, the most significant factors for the failure probability of reflective cracking are the HMA thickness and removal thickness. The HMA thickness is the overlay thickness for the rehabilitation treatment, and the removal thickness is the milled asphalt concrete depth. In Figure 5 (a), the failure probability drops heavily as the thickness increases. Traffic level is not a significant factor. However, higher traffic levels do accelerate the propagation of reflective cracking as shown in the failure probability profile.

Heater Scarification

In Figure 5 (b), the most significant factor for the initiation of reflective cracking is the overlay thickness. A greater removal thickness does retard the crack development, but it is not significant. Higher traffic can accelerate the propagation of reflective cracking but not significantly, as shown in the distribution profile.

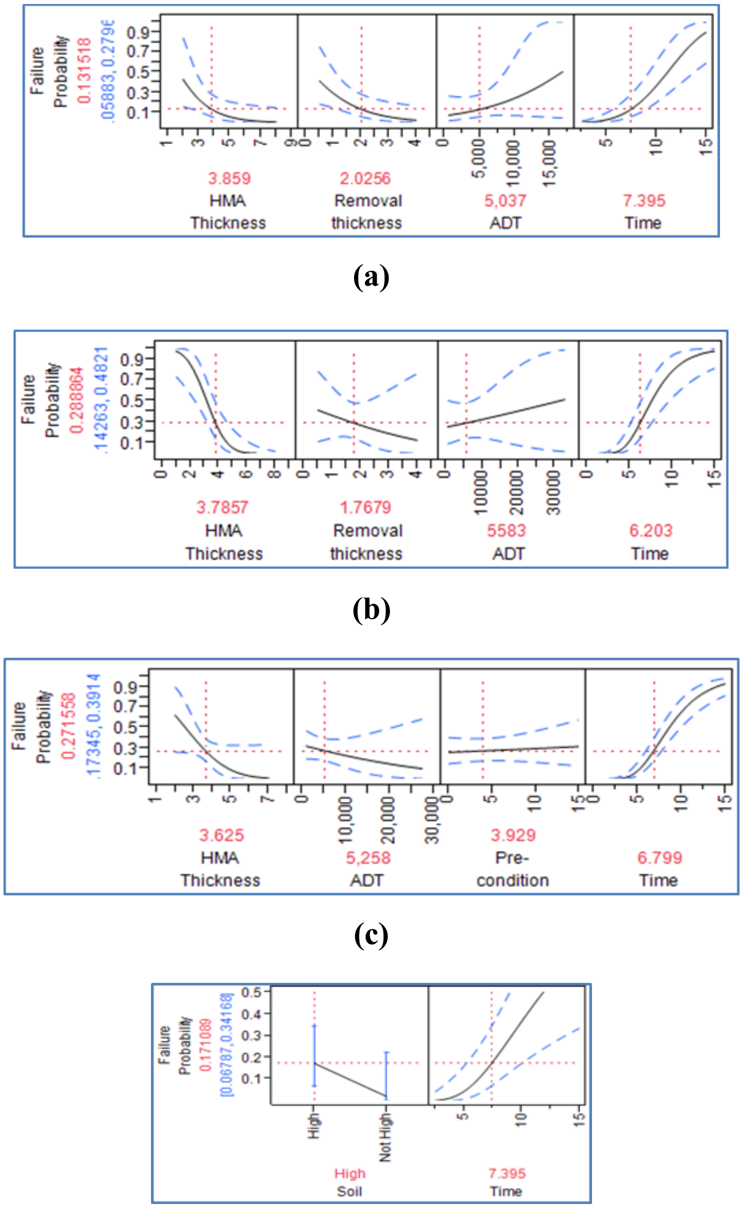
Overlay

Pavement structural overlay does not require a pre-removal construction process. Therefore, the pre-treatment condition before an overlay is involved and checks whether a poor pavement condition on the old layer can be reflected into the new overlay. However, Figure 5 (c) shows that the pre-condition and failure function are horizontally related, which means that the pre-condition does not affect reflective cracking in the new overlay.

Rubblization

Many of the rubblization projects are in the county roads. The county road IPMP database does not contain pavement thickness and traffic information. Therefore, these factors are not evaluated. Instead, researchers have found that the early failure behind rubblization could be more related to the subgrade drainage and soil properties (16). This is because during the concrete pavement rubblization process rapidly high pore-water pressure could be generated and damage the road subgrade in poor drainage condition. In this study, soil types at the project locations are investigated using the data from the

National Cooperative Soil Survey System. This system provides an interactive digital map that makes it easy to identify the project locations. The soil types in these projects locations are divided into two groups: high silt-clay region and non-high silt-clay region. The high silt-clay region is for the terrain that reported to have more than 60% poor drained silty clay or clay loam. Figure 5 (d) shows that the soil type does not significantly influence the rubblization pavement performance. Modifying the rubblizing pattern to produce large particle sizes (e.g. light rubblization and multiple-head breaker), commonly used in Iowa could provide an alternative and compensate for a weak and poor-drained subgrade.



(a)

(b)

(c)

(d)

FIGURE 5 Influence Factors on Reflective Cracking for Mill & Fill (a), SCR (b), Overlay (c), and Rubblization (d)

RECOMMEDATION & CONCLUSION

This paper has successfully outlined a method for understanding the performance of four pavement rehabilitation methods of traditional composite pavements, e.g. hot mix asphalt over PCC pavement. A large set of data from in-service pavements is used in conducting survival analysis to evaluate the performance of four different composite pavement rehabilitation methods. These include mill & fill, asphalt concrete overlay, rubblization and heater scarification. Several conclusions are summarized as follows:

- The Kaplan-Meier estimator clearly illustrates that pavement rubblization can significantly retard reflective cracking development in composite pavements compared with the other three methods.
- The hazard/failure function for reflective cracking tends to follow the Lognormal distribution that has an early time increase before being constant or decreased. The corresponding survival function shows a quick drop with a long tail in the later service life.
- No significant differences on PCI are seen in the survival analysis for the four rehabilitation methods.
- The heater scarification method shows the lowest survival probability on reflective cracking and IRI. The use of RAP could contribute to the acceleration of reflective cracking and a higher IRI initial value could be attributed to the shorter service life on IRI.
- Traffic level is not a significant factor for reflective cracking investigated in this multivariate analysis. However, higher traffic level shows the trend to accelerate the cracking development.
- Greater pavement thickness (both overlay and removed thickness) is effective in retarding the propagation of reflective cracking.
- Statistics show that subgrade soil property can influence the use of rubblization in the field. However, modifying the rubblization pattern to compensate for weak subgrade is a commonly held belief by practitioners.

ACKNOWLEDGMENTS

The authors would like to thank the Iowa Highway Research Board and the Iowa Department of Transportation for the financial and technical support associated with this research project. The authors also recognize and appreciate Dr. Omar Smadi who provided the IPMP database information. Finally, Thanks to Antigo Construction Company that provided logistical support and information for the rubblization projects.

REFERENCES

1. Von Quintus, L.H., Mallela, J., and Lytton, L.R. *Techniques for Mitigation of Reflective Cracks.* Presented in 2010 FAA Worldwide Airport Technology Transfer Conference, Atlantic City, 2010.
2. Lytton, L.R., Tsai, L.F., Lee, S.I., Luo, R., Hu, S., and Zhou, F.J. *NCHRP Report 669: Models for Predicting Reflection Cracking of Hot-Mix Asphalt Overlay.* National Cooperative Highway Research Program, 2010.

3. Federal Highway Administration (FHWA). *Pavement Recycling Guideline for State and Local Governments Participant's Reference Book.* Publication No.: FHWA-SA-98-042. FHWA, U.S. Department of Transportation, 2002.
4. Zhou, L., Ni, F.J. and Zhao, Y.J. Evaluation Method for Transverse Cracking in Asphalt Pavements on Freeways. *In Transportation Research Record*, No.2153, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp.97-105.
5. Smadi, G.O. and Maze, H.T. Developing Iowa's Statewide Pavement Management Program. *4th Interntaional Conference on Managing Pavements*. 1998.
6. Bausano, J.P., Chatti, K., and Williams, R.C. .Determining Life Expectancy of Preventive Maintenance Fixes for Asphalt-Surfaced Pavements. *In Transportation Research Record* No.1866, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 1-8.
7. Dong Q. and Huang B.S. Evaluation of Influence Factors to Crack Initiation of LTPP Resurfaced Asphalt Pavements Using Parametric Survival Analysis. *In Transportation Research Board,* CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2011. Paper #11-2723.
8. Yang, J.D. Development of Effective Remaining Life Prediction Models for Pavement Management at the Network Level. *In Transportation Research Board*, CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2009. Paper #09-0960.
9. Hosmer Jr., W. D. and Lemeshow, S. *Applied Survival Analysis: Regression Modeling of Time to Event Data.* John Wiley & Sons, Inc., 1998.
10. Papagiannakis, A., Gharaibeh, N., Weissmann, J., and Andrew W. *Pavement Scores Synthesis.* Report No.: FHWA/TX-09/0-6386-1. Texas Transportation Institute.
11. Titus-Glover, L., Fang, X.C., Alam, M., O'Toole, K., and Darter, M. *Pavement Health Track, Remaining Service Life Forecasting Models, Technical Information.* Publication by Federal Highway Administration Office of Asset Management, Washington, D.C., 2010.
12. Timm, H.D. and Warren, M.A. *Performance of Rubblized Pavement in Alabama.* Publication No. IR-04-02. Alabama Department of Transportation, 2004.
13. *JMP User's Guide Version 9: Quality and Reliability Methods.* SAS Campus Drive, Cary, North Carolina.
14. Gharaibeh, N.G. and Darter, M.I. Probabilistic Analysis of Highway Pavement Life for Illinois. *In Transportation Research Board*, CD-ROM. Transportation Research Board of the National Academies, Washington, D.C., 2003.
15. Akaike, H. *A new look at the statistical model identification*, IEEE Transactions on Automatic Control 19 (6): 716–723, 1974.
16. Battaglia, I.K., and Paye, B. (2011). *Investigation of Early Distress in Wisconsin Rubblized Pavements*. Report No. WI-02-11. Wisconsin Department of Transportation, 2011.