Transportation Research Part C 68 (2016) 58–69

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Development of distress condition index of asphalt pavements using LTPP data through structural equation modeling

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ARTICLE INFO

Article history:
Received 21 November 2015
Received in revised form 29 March 2016
Accepted 30 March 2016

Keywords:
Structural Equation Modeling (SEM)
Latent variable
Endogenous and exogenous variables
Pavement distress condition index
Long-term Pavement Performance (LTPP)
Multiple regression model

ABSTRACT

Traditional pavement distress index such as the Pavement Condition Index (PCI) developed by U.S. Army Corps of Engineers determines coefficients of distresses based on subjective ratings. This study proposed an asphalt pavement distress condition index based on various types of distress data collected from the Long-Term Pavement Performance (LTPP) database through Structural Equation Modeling (SEM). The SEM method treated the overall distress index as a latent variable while various distresses were treated as endogenous and other influence factors such as age, layer thickness, material type, weather, environment and traffic, were exogenous observed variables. The SEM method modeled the contributions of various distresses as well as the influence of other factors on the overall pavement distress condition. Influences of age, layer thickness, material type, environment and traffic on the latent distress condition were in accordance with previous studies. Compared with previous attempts to model latent pavement condition index utilizing SEM method, more pavement condition measurements and influencing factors were included. Specifically, this study adopted the robust maximum likelihood estimator (MLR) to estimate parameters for non-normally distributed data and derived the explicit expression of latent variables with intercepts. A multiple regression prediction model was built to calculate an overall condition index utilizing those measured distress data. The established pavement distress index prediction model provided a rational estimation of weighting coefficients for each distress type. The prediction model showed that alligator cracking, longitudinal cracking in wheel path, non-wheel path longitudinal cracking, transverse cracking, block cracking, edge cracking, patch and bleeding were significant for the latent pavement distress index.

1. Introduction

1.1. Background

Pavement condition evaluation has been playing a vital role in both pavement rehabilitation design and highway asset management. Accurate diagnosis of pavement distress condition gives engineers more clues on choosing proper repair

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http://dx.doi.org/10.1016/j.trc.2016.03.011

methods at the project level, estimating pavement network condition, predicting performance (Chu and Durango-Cohen, 2007; Karlaftis and Badr, 2015; Mariani et al., 2012) and making maintenance decision. Recent advancements in automatic pavement distress data collection, such as high precision laser scanning and camera image processing technologies, enable the interpretation of more detailed pavement distress data, which presents critical challenges for highway researchers and engineers on the correct utilization of huge amount of collected data to build a rational pavement distress index for better pavement management and maintenance decision making.

The first pavement performance index is the Present Serviceability Rating (PSR), developed by American Association of State Highway Officials (AASHO) (Carey and Irick, 1960). It is a subjective rating based on users' experience and judgment. On the basis of PSR, pavement roughness, patching, rutting and cracking, Present Serviceability Index (PSI) was derived (Carey and Irick, 1960; Hall and Muñoz, 1999). As the development of pavement survey technology such as laser profiler and digital image processing, a vast amount of detailed pavement condition data regarding different types of distresses became available. Engineers have been trying to define an overall pavement distress index based on observed specific distresses. The U.S. Army Corps of Engineers (USACE) proposed the Pavement Condition Index (PCI) (ASTM D6433-99, 1999), which is calculated by subtracting deduct values of distresses with various severities and extents from a full score. The deducted values, or weighting coefficients, are determined by experts' opinion, or empirical engineering criteria. Meanwhile, many state Departments of Transportation (DOTs) have developed their own distress condition indices including the distress-index such as TxDOT's DS and CS, Ohio DOT's PCR, Oregon DOT's OI, South Dakota DOT's SCI and Pennsylvania DOT's OPI (Gharaibeh et al., 2009).

Plenty of studies have been conducted to propose new pavement condition indices or modify the existing ones through various methods. Among those studies, many critical coefficients were determined through expert surveys (Eldin and Senouci, 1995; Jackson et al., 1996; Juang and Amirkhanian, 1992; Koduru et al., 2010; Saraf, 1998; Sun and Gu, 2010). For instance, Juang and Amirkhanian (1992) proposed the unified pavement distress index (UPDI) to measure the pavement distress condition. Six types of distresses were rated and weighted through the survey of opinions and experience of most state highway departments. Eldin and Senouci (1995) computed the pavement condition rating based on the cracking and rutting indices. The coefficients which represented the relative importance of the type and severity of each distress were determined by experience and judgment of highway engineers and maintenance personnel. For the aspect of condition evaluation methods, the fuzzy logic method which can analyze linguistic or non-crisp data and the uncertainty of data was utilized to evaluate the pavement condition by considering the severities, densities and weighting factors of different distresses (Bianchini, 2012; Golroo and Tighe, 2009; Juang and Amirkhanian, 1992; Karaşahin and Terzi, 2014; Koduru et al., 2010; Pan et al., 2011). The relative importance of each distress in fuzzy logic method was usually empirically determined. As for the others, Zhang et al. (2003) proposed the Structural Condition Index (SCI) (the ratio of existing SN to required SN) to discriminate pavement structural condition. Park et al. (2007) established the power regression model between PCI and IRI and the results showed that the variations in IRI can explain the majority of the variations in PCI.

As can be summarized from previous researches, the weights of those distress indicators or the rankings in fuzzy logic method were determined based on engineering judgment. Thus, the objective pavement condition evaluation is very important. In addition, many transportation agencies use weighted sum or deduction of various pavement distresses as an overall pavement condition index. It is expected that the overall index could reflect the pavement condition and produce a reasonably smooth curve matching trends of observed distress. Therefore, it is of great interest to investigate the relationships among measured distress indicators and the pavement condition which cannot be directly observed or represented by a single distress indicator. A more rational evaluation of the pavement performance driven by the data will help improve the maintenance of transportation infrastructures.

1.2. Structural Equation Model (SEM)

Structural Equation Modeling (SEM) is a statistical approach to deal with the relationship between unobserved or latent variables and observed variables which are measured to reflect the latent variables (Khine, 2013; Kline and Santor, 1999). It can handle the complex relationships among latent and observed variables simultaneously (Hassan and Abdel-Aty, 2011; Lee et al., 2008). SEM includes two components, the measurement model and structural model. The measurement model reveals how well various observed variables measure latent variables. The structural model describes how the latent variables are related to one another.

The SEM method was firstly proposed by Wright (1918). Since the 1970s, it has been drawing the attentions of researchers to address a variety of questions in psychology, education, sociology and econometrics. It was widely used in those areas to analyze the variable that is not easily and directly observed or measured (Khine, 2013; Proitsi et al., 2011; Wang and Wang, 2012). For example, scientists used SEM to find how well students' scores reflect their math ability. In addition to the social science field, SEM has been introduced and adopted in the engineering field as an emerging technology in the past decades. In the area of transportation engineering, Mokhtarian and Meenakshisundaram (1999) used SEM to identify the interrelationships among different communication modes including electronic communications, personal meetings and transfer of information objects. Cheng and Huang (2013) adopted SEM to investigate the impact of metal accounting theory and technology acceptance model on consumers' decision to adopt mobile ticketing. Sasaki and Nishii (2010) investigated the relationships between the number of trips/telecommunications and various trip/telecommunication factors including telephone call/receiving, e-mail sending/receiving and weekdays or weekends through SEM. Jou et al. (2011) adopted