

APPLICATION OF ROAD DETERIORATION SIMULATION MODEL FOR
PREDICTING INITIATION AND PROGRESSION OF CRACKS ON ROAD
PAVEMENT

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To my beloved wife, sons, father and mother

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ABSTRACT

In order to be able to predict the life-cycle of road pavement, a model that is capable of predicting any changes of road pavement condition in future is needed. The model should consider the current condition, pavement strength, age characteristics, environment, incremental time and incremental traffic. The aim of this study is to investigate and to develop a simulation model that can predict road pavement deterioration for flexible pavement on rural single carriageway roads. Priority of the model is initiation, development and progression of cracking. The aim of the study can be achieved by developing a computer simulation model that can predict road deterioration and road performance. This research developed coefficients of each model that agree to local condition based on observed data that were collected for 1.5 years. The simulations show that in general model of vehicle arrival are Poisson distribution. In addition, it was discovered that the development of crack was not individual but there was a relationship between each type of crack. These models were able to predict progression of cracking with $R^2 = 0.5925$ to 0.8765 which were more appropriate than the existing model. The coefficients of crack initiation model were different than the existing models that were 5.7% to 20% for AMAP (Asphalt Mix on Asphalt Pavement), 2.8% to 16.2% for AMSB (Asphalt Mix on Stabilized Base) and 1.6% to 2.2% for AMGB (Asphalt Mix on Granular Base). While progression of cracking are 8% to 75% for AMAP (Asphalt Mix on Asphalt Pavement), 4% up to 16.6% for AMSB (Asphalt Mix on Stabilized Base), 0% to 25.6% for AMGB (Asphalt Mix on Granular Base). In addition, the cracking model can be used as guide for maintenance intervention criteria.

ABSTRAK

Untuk meramalkan jangka hayat bagi jalan raya, ia memerlukan satu model yang boleh meramalkan perubahan keadaan jalan raya pada masa yang akan datang. Model tersebut perlu menggunakan ramalan yang menimbangkan keadaan terkini, ciri-ciri kekuatan jalan raya, usia, alam sekitar dan trafik. Tujuan penyelidikan ini adalah untuk mengenalpasti dan menghasilkan simulasi pemburukan jalan raya untuk pengerasan anjal jalan raya luar bandar. Keutamaan adalah pada keretakan yang mana untuk menentukan masa bermulanya keretakan itu dan untuk meramal model bagi perkembangan keretakan. Tujuan penyelidikan boleh dicapai dengan membuat model komputer simulasi yang boleh meramalkan memburuknya jalan raya dan prestasi jalan raya. Penyelidikan ini untuk membangun pemalar baru yang sesuai untuk keadaan tertentu berdasarkan data kerosakan jalan yang diamati selama 1.5 tahun. Simulasi ini menunjukkan model umum taburan ketibaan kenderaan adalah bercorak taburan Poisson dan pembentukan keretakan tidak disebabkan oleh satu jenis keretakan tetapi terdapat hubungan antara jenis-jenis keretakan tersebut. Model ini mampu meramalkan perkembangan keretakan, dengan tingkat kesesuaian $R^2=0.5925$ hingga 0.8765 lebih sesuai daripada model asal. Pemalar yang diperoleh untuk masa bermulanya keretakan terdapat perbezaan dengan model asal ialah 5.7% hingga 20% untuk AMAP (Asphalt Mix on Asphalt Pavement), 2.8% hingga 16.2% untuk AMSB (Asphalt Mix on Stabilized Base), 1.6% hingga 2.2% untuk AMGB (Asphalt Mix on Granular Base). Sedangkan untuk perkembangan keretakan terdapat perbezaan dengan model asal ialah 8% hingga 75% untuk AMAP (Asphalt Mix on Asphalt Pavement), 4% hingga 16.6% untuk AMSB (Asphalt Mix on Stabilized Base), 0% hingga 25.6% untuk AMGB (Asphalt Mix on Granular Base). Sebagai tambahan, model keretakan boleh digunakan untuk tuntunan dalam kriteria memelihara jalan

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LIST OF SYMBOLS

AADT	-	Annual Average Daily Traffic
AASHTO	-	American Association of State Highway and Transportation Officials
AC	-	Asphalt Concrete
ACX	-	Area of Structural Cracking
ACT	-	Linear Transverse Crack
ACRW	-	Wide Cracking
AGE	-	Pavement Surface Age
AM	-	Asphalt Mix
AMAB	-	Asphalt Mix on Asphalt Base
AMAP	-	Asphalt Mix on Asphalt Pavement
AMSB	-	Asphalt Mix on Stabilized Base
AMGB	-	Asphalt Mix on Granular Base
AND	-	Annual Number of Day $> 32^{\circ}\text{C}$
ANNPRE	-	Annual Precipitation
APOT	-	Pothole Area
AI	-	Asphalt Institute
AVIS	-	Asphalt Viscosity
AWP	-	Axle wheel Path
a_0 to a_5	-	Coefficient depending on pavement type
BB	-	Benkelman Beam
Bt	-	Block Crack at given period
Bt-1	-	Block Crack at Previous Period
C	-	Crack
CBR	-	California Bearing Ratio

CL	-	Centre Line
Cm	-	Centimeter
COMP	-	Compaction
CQ	-	Construction Quality
CRX	-	The incremental Area of Cracking
CW	-	Carriageway Width
CESA	-	Cumulative Equivalent Standard Axle
CRKSPACE	-	Crack Space (Spacing between transverse crack)
DEFL.	-	Deflection
ESA	-	Equivalent Standard Axle
ES	-	Edge Side
FI	-	Freezing Index
HDM	-	Highway Design and Maintenance Standards Model
HB	-	Thickness of Base
HGV	-	Heavy Good Vehicle
HRA	-	Hot Rolled Asphalt
HS	-	Thickness of Surface
HS	-	Thickness of Layer
HSNEW	-	Thickness of New Surface
HSOLD	-	Thickness of Old Surface
ICX	-	Crack Initiation
IRT	-	Initial of Rutting
IRV	-	Initial of Ravelling
IPT	-	Initial of Potholing
IDL	-	Initial of Delamination
IRI	-	International Roughness Index
IWP	-	Inner Wheel Path
Kg	-	Kilogram
Km	-	Kilometer
Kci	-	Crack Initiation Factor
KCP	-	Crack Progression Factor

LD	-	Lane Distribution
LB	-	Large Bus
LF	-	Load Factor
LTPP	-	Long Term Pavement Performance
Lt-1	-	Long Crack at Previous Period
M	-	Meter
MAC	-	Modified Asphalt Cement
MMP	-	Mean Monthly Precipitation
MS	-	Marshall Stability
NAASRA	-	National Association of Australia State Road Authorities
OP	-	Observation Point
OWP	-	Outer Wheel Path
P	-	Pothole
PACA	-	Pre-overlay per cent Crack Area
PACX	-	Pre-overlay per cent Area of Structural Crack
PACT	-	Pre-overlay per cent Area of Thermal Crack
PACR	-	Pre-overlay per cent Area of Reflection Crack
PCU	-	Passenger Car Unit
PSI	-	Present Serviceability Index
PSR	-	Present Serviceability Rating
RD	-	Rut Depth
RDPD	-	Rut Depth Plastic Deformation
RDM	-	Rut Depth Mean
RDS	-	Rut Depth Standard Deviation
RDST	-	Rut Depth Structural
RF	-	Regional Factor
SB	-	Small Bus
SBST	-	Single Surface Treatment
SIM	-	Simulate
SL	-	Slurry seal
SMA	-	Stone Mastic Asphalt

SN	-	Structure Number
SNC	-	Structure Number Composite
SNP	-	Structure Number Pavement
SP	-	Softening Point
ST	-	Surface Treatment
TCI	-	Time Cracking Initiation
TR	-	Trailer
TF	-	Truck Factor
Tt-1	-	Transversal Crack at Previous
VMA	-	Void in Mix Aggregate
VIM	-	Void In Mixture
WIM	-	Weight In Motion
YE4	-	Annual Cracking Loading
χ^2	-	Chi (The null hypothesis)
t	-	Time
r	-	Traffic Growth
r^2	-	Determination coefficient
e	-	Exponential
z	-	Sigmoidal model parameter

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CHAPTER 1

INTRODUCTION

1.1 Background

The service life of a road may decrease to an acceptable minimum level, both functionally and structurally after the road has been opened and subjected to traffic load. The functional condition of a pavement is usually measured quantitatively in term of Present Serviceability Index (PSI) at any particular time. PSI is calculated as a function of rutting, cracking, and patching as well as longitudinal unevenness.

A new-paved road can deteriorate very slowly and almost imperceptibly at the beginning of his life, and then worsen much more rapidly unless the timely maintenance is undertaken. Nevertheless, this study is more concerned on the deterioration of an aging road infrastructure and how best to control it.

In order to avoid such a sharp rise in the demand of highway expenditures, it is necessary to develop and implement an improved road management and planning system. The system is required to estimate the time and financial needs of the road maintenance and rehabilitation programs, as well as to evaluate the design and maintenance standards appropriate to the funding available to the highway sector and plan, and to prioritize works in a program.

As soon as the pavement is opened to traffic it start to deteriorate. The road will need maintenance and improvement so that it can continue to function throughout its expected design life and or extended service life in accommodating the traffic load.

There are three maintenance approaches. First, ad hoc approach, this is an incidental solution that is suitable for small direct maintenance so that there is no planning and budget orientation. Second, the present condition approach based on a short term planning to manage the road network. Third, the life cycle approach which is the best way to manage the road network that can support the over all management system of pavement from planning until implementation. The life cycle approach includes prediction of future condition, optimal time of application, and identification of the best maintenance and rehabilitation alternative.

Managing effectively and efficiently a road network with different types and levels of distress are difficult to define as the road deteriorates through a variety of different mechanisms for each type. The increasing demands for improved management and planning techniques and for maintenance cost require more exact mathematical modeling of the road deterioration. Nevertheless, a mathematical model of road deterioration is an essential component of any road management system.

There are three indicators that representing the performance of an asphalt pavement: cracking, disintegration, and permanent deformation. Since cracking is one of the important distresses in an asphaltic pavement, the objective of a primary asphaltic pavement design is to minimize cracking as it often causes the application of maintenance treatments.

This study focuses on the development of mathematical model of road deterioration prediction and analyzes a pavement performance under load that is influenced by the environment, and structure properties. The model developed is a simulation that consists of traffic and road deterioration simulation. The analysis is primarily focused on empirical models of crack initiation and progression of asphalt pavement.

1.2 Problem Statement

The primary objective of both pavement design and maintenance is to ensure that the pavement gives adequate service to the road user. The performance of the pavement is measured in terms of the quality of provided service and achievement of the acceptable levels of service. The concept of serviceability of a pavement was defined by Haas and Hudson (1978) as quantifying the subjective measure of the level of service for users and providing a basis for relating service to various physical measures of pavement condition.

The deterioration of paved roads is defined by the damage trend of its surface condition over time. The defects of a pavement surface, which are usually quantified through a pavement condition survey, are classified under three major modes of distress, namely, cracking, disintegration, and permanent deformation.

In the life-cycle predictions, the model need to predict the expected change of condition in the future over a given period of time or the transit of one extra axle load providing that the current pavement condition is known. Thus the model should be essentially in the incremental and recursive form and the change of condition, namely; current condition, pavement strength, age characteristics, environment, incremental time, and incremental traffic are considered.

Predictive model is a kind of statistical correlation that correlate distress (as a dependent variable) to a various pavement, traffic, and environment condition (the explanatory variables). The model of road deterioration is developed from both, the traffic and road damage simulation to form an empirical study that are a mechanistic (mechanistic model) and stochastic variation effect approach.

Road deterioration is the main variable that is predicted and it depends on the other variables. The Transport Research Laboratory (TRL) and the Institute of Road Engineering (IRE) have been working together in the highway engineering and road management field since 1975, (Paterson *et al.*, 1987 and Bennett *et al.*, 1995) on Design and Maintenance standards (HDM-III and HDM-IV respectively) provides road deterioration models and road user cost model. The HDM-III and HDM-IV model

contain relationships for predicting road deterioration and maintenance effect as functions of pavement characteristic, traffic, and the environment (Watanatada *et al.*, 1987). The road deterioration relationships in existing model (Bennett *et al.*, 1995) are either that previously (Paterson *et al.*, 1987) have some shortcoming in the deterioration analysis, i.e., (a) The dominant model that has been analyzed was fatigue (b) the models are individual which no correlation among each types of crack, so that those must be reviewed and modified or developed to predict the appropriate road deterioration.

Furthermore, the need for advanced analysis of how to predict damage caused by incremental traffic and load which are influenced by current condition, pavement strength and age characteristic, environmental, and incremental time is prompted due to importance to know the correlation between the pavement character or behavior and pavement distress, traffic, and time and also the correlation between the road performance, in PSI, and time.

1.3 Aim and Objectives

In view of the need for a better understanding of road deterioration and pavement behavior under traffic repetition and environmental conditions, the aim of the study is to develop a computer simulation model that can predict road deterioration process and to relate the types of road damages to the age and traffic conditions. This study is designed to achieve the following objectives;

- (i) to develop an empirical model for predicting the crack initiation and progression for asphalt pavement,
- (ii) to develop empirical model for predicting the mechanism (interaction) of crack development.

1.4 Scope of the Study

This research focuses on flexible pavement on rural single carriageway, and the priority is on crack damage that predicting the crack initiation and progression that consists of:

- (i) the traffic simulation on the single carriageway road,
- (ii) the simulation of road deterioration which is influenced by the traffic load repetition, pavement factor, and environmental,
- (iii) the calibration and validation of the existing mathematical model of the road deterioration using the performance data coming from monitoring section.

1.5 Limitations

In view of the broad nature of the problem that will be discussed and the limited time available to conduct the research, the data obtained was quite limited, so the study needs limitations to achieve the representative results. The limitations are:

- (i) this research focused on the simulation study of the road deterioration prediction and the development or evaluation of the model for predicting the initiation and progression of crack for flexible pavement on single carriageway with two lanes,
- (ii) primary data was obtained from the new road, Jalan Lintas Timur Sumatera of Km 64 + 000 u/t Km 65 + 000 (Kandis – Duri) and from the existing road of Km 110 + 000 u/t 145 + 000 (Simpang Lago – Simpang Japura) and from the existing road of km 74 + 000 U/t 78 + 000 (Kandis – Duri), Riau, Indonesia, and the observation took in a short time (12 months),
- (iii) densification and deformation in the sub grade layer and driver's characters are ignored,
- (iv) the model derived from mechanistic and probabilistic data is based on Paterson's study (1987) and Bennett, *et al.*, (1995).

1.6 Layout of the Thesis

Chapter 2 reviews the importance of the research or field investigation and the previous modeling approach of pavement distress to provide rationale of the prediction. Characteristics of the pavement structure, pavement distress, environment, and traffic are described in this chapter. The magnitudes of the stresses and strains induced in a pavement that cause road damages are not easily achievable. However, numerous field investigations have been performed to develop relationship between distress and deflection that influence traffic and environment. Therefore, it is possible to relate empirically future performance of pavement structure under road traffic since HDM IV, HDM-III, LTPP, and TRRL modeled the concept of the road damage prediction.

Chapter 3 describes the methodology and data collection which consists of study approach and process activities. The study consists of five main sections: literature review, collecting data, seminar proposal, development of intelligent model, and model calibration. The chapter also outlines the processes of the activities of the study, especially in collecting data, developing model, calibrating, and validating.

Chapter 4 discusses the data collection and analysis of the site studies of the road damages, traffic, and environment. The monitoring sections were located on three routes that consist of one new road (surface layer) and two existing roads. The data collection of the road damages were gathered at three different time intervals. Each period took 6 months to complete (March 2002, September 2002, and March 2003).

Chapter 5 presents the model development. This chapter provides the details of the processes for the model development. The traffic simulation model was developed with DELPHI program using a cellular “automata” method that is based on microscopic approach (individual approach). The damage prediction model refers to the Paterson *et al.*, (1987) and Bennett *et al.*, (1995) that was associated with HDM-III and HDM-IV model that contain relationship between the road deterioration prediction and the maintenance effect derived primarily from pavement performance study in Brazil.

Chapter 6 outlines the process used for calibrating and validating the model development in this study. The model development comprises of two main models; first, traffic model that consist of road model and traffic model and second, the road damages prediction model that is separated from traffic simulation model. The components of road deterioration simulation i.e., (a) equation to count road damages and road performance (b) structural reference (c) axle data (d) result of damage prediction. The traffic model are calibrated using previous models i.e., (a) vehicle arrival distribution (b) time-distance diagram (c) drivers car following distance and validated using the monitoring results in three periods. The road deteriorate model are calibrated and validated using road damage data from monitoring result at different time intervals.

Chapter 7 explains the application of the developed simulation model to predict road performance and road deterioration in the future especially in the initiation and progression of cracking. Feedback from the model is essential for verifying and improving the design methodologies.

Chapter 8 summarizes the thesis and the findings of the study. Several important areas of the research are recommended for the future research.

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