Pavement Performance Prediction Model Development for Tehran

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Abstract

Highways and in particular their pavements are the fundamental components of the road network. They require continuous maintenance since they deteriorate due to changing traffic and environmental conditions. Monitoring methods and efficient pavement management systems are needed for optimizing maintenance operations. Pavement performance prediction models are useful tools for determining the optimal time for these actions. However, incorporating the model components into a pavement management system is highly important to ensure the model efficiency. This paper presents the existing pavement performance prediction models and introduces their components. A specific model is reproduced for Tehran traffic and environmental conditions adapted from the Pavement Health Track (PHT) model. This new model comprises four different sub-models including crocodile cracks, rutting, transverse cracking, and roughness prediction models. The study presents the software tool industrialized based on the model and presents the associated calibration and validation. Validation of the model for Tehran city shows that this new model has a high prediction accuracy. Also, it is a practical tool for pavement condition predictions across Tehran as it needs fewer data requirements compared with other complicated models. This study shows that using the new model may lead to an organized maintenance budgeting as well as a decrease in time and cost of operations.

Keywords: Pavement distresses; pavement management system; pavement performance; prediction model; PHT model; roughness.

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1. Introduction

The quality and extent of the transport systems are considered as important indicators of a country's development. The road network infrastructure has a fundamental role in this industry [Taherkhani and Afroozi, 2017]. The road network is deemed to be a country's lifeline with a considerable part of the annual national budget spent on its development and maintenance [Ameri, 2008]. Pavements are important components of road networks and need continuous maintenance. Studies have demonstrated that poor pavement conditions contribute significantly to increasing the travel time and decreasing road safety, leading to numerous accidents [Taherkhani, 2016].

Necessary resources and operations can be predicted by understanding the process of reducing pavement service. The allocation of sufficient funds for maintenance of pavements is a constant challenge that the decision-makers need to deal with [Semnarshad and Saffarzadeh, 2018]. In fact, predicting and determining the optimal amount of funds for this operation is extremely complicated and difficult, and needs an effective pavement management system [Molenaar, 2003]. The capability of estimating future pavement performance based on the existing condition and presenting preventive operations are the important criteria of an efficient pavement management system [Kerali, 2004].

A modern pavement management system should include definitions for different types of distresses and effective repair and rehabilitation methods. This system should also have methods for prioritization of pavement maintenance measures to help predict funding for these operations [Semnarshad and Saffarzadeh, 2018]. There is always an optimal time for maintenance and rehabilitation operations. Deterioration rate and maintenance costs will decrease if timely operations are not carried out. Pavement performance prediction models are the best tools for this optimal time determination [Kerali, 2004]. Such a model should express the distressing process comprehensively and consider all the influential factors [Ameri, 2008].

There are many kinds of pavement performance prediction models each having its own structure. A major difference between these models is their estimation accuracy and data requirements. It is difficult to estimate the exact pavement life because determining the effectiveness of the factors included in the model is not an easy task [Haas et al., 1994]. HDM-III, HDM-4, Markovian models, artificial neural network models, and the PHT model are the basic pavement performance models [FHWA, 2013]. Developing a pavement performance prediction model for Tehran is the main purpose of this research.

This paper presents a background of the modern pavement management system. It discusses the required data for model calibration and existing data leading to model selection for specific conditions in Tehran. After presenting the calibration and validation process and the associated outcomes, it introduces the developed software and shows its outputs.

2. Literature Review

In 1967, the first attempt to develop the PMS in the field of pavement systems engineering was undertaken by NCHRP. In 1989, FHWA attempted to create the first pavement management system. This program aimed to have each FHWA office define a PMS for themselves by 1993. Maintenance planning and pavement management systems gradually developed in many countries [Behbahani, 2004] over this period. There were some major themes amongst the pavement prediction models. Many of the models were developed using these themes. These themes will be discussed below.

HDM-III, as the third-generation release of the HDM model, is a deterministic model for predicting pavement performance [Abaynayaka et al., 1977; Watanatada et al., 1987]. This model is based on roughness, traffic, and environmental data. Pavement condition is predicted by cracking, raveling, potholing, rutting and International Roughness Index (IRI) [Watanatada et al., 1987; Babashamsi et al., 2016]. The HDM-III model has several disadvantages including:

- Functional limitation and low prediction accuracy, [Abaynayaka et al., 1977; Kerali, 2004]
- Very poor prediction accuracy in the rutting model [Abaynayaka et al., 1977], and
- Independence from increasing the traffic volume [Kerali, 2004; Abaynayaka et al., 1977].

The HDM-III has been used for two decades. The international study of highway development (ISOHDM) has been carried out to extend the scope of this model and to provide a harmonized system approach to road management. This has produced the Highway Development and Management Tool (HDM-4). This new model is more accurate than HDM-III. Also, a broader range of distress is included in this model compared to other deterministic models. HDM-4 has also several weaknesses including [Kerali, 2004]:

- The extent of the required data
- Less prediction accuracy than the new models (like PHT or ANN)
- The same impact of distresses and roughness

Markovian model is a probabilistic model, widely used for developing pavement performance prediction models. This model is based on the Pavement Condition Index (PCI) and a wide range of distresses [Butt et al., 1987]. This model has several shortcomings including [Butt et al., 1987]:

- There is no software ready for use
- Complex calculation and high Executive time [Babashamsi et al., 2016]
- Less prediction accuracy than the new models like the PHT or ANN

The Artificial Neural Network model is based on IRI, PCI and a wide range of distress measures. This model was firstly developed in Texas in 1999. It has high prediction accuracy and is easily expandable [Bosurgi and Trifirò, 2005]. This model has several weaknesses including [Bosurgi and Trifirò, 2005]:

- The extent of the required data
- Complex calculation and high executive time

The PHT is a deterministic model for predicting pavement performance. It is a modern model with a structure similar to the HDM-4 but with less data requirements than those which are necessary for HDM-4 [FHWA, 2013]. This model has several strengths including [FHWA, 2013]:

- Effective participation of traffic parameters
- Low data requirement
- No similar effects for distresses and roughness
- Modern and advanced software

It is believed that a model with higher prediction accuracy and the least data requirements, like the PHT, is an appropriate choice for Tehran. This issue will be discussed in more detail, later in this paper.

Some attempts in developing pavement management systems appropriate for Iran, have been undertaken. These are briefly introduced in the following.

Flexible Pavement Management Research Tool (FPMRT) is a pavement management system developed at Sharif University of Technology [Tabatabaee and Saliminejad, 2009]. The program is designed using commercial Windows components with a user interface that follows standard Windows protocols. FPMRT assists pavement managers in deciding when and where to allocate funds for pavement maintenance and rehabilitation purposes. FPMRT provides pavement management capabilities to [Tabatabaee and Saliminejad, 2009]:

- Develop and organize pavement inventory.
- Assess the current conditions of pavements.
- Report past and present pavement performance.
- Develop scenarios for pavement maintenance based on budgetary or other requirements.
- Compare different methods to choose the most effective one by providing users with alternative methods.

FPMRT contains six major components. They are: 1) segmentation; 2) pavement distress analysis; 3) skid resistance analysis; 4) Maintenance and Repair (M&R) assignment to pavement segments; 5) M & R budget prioritization/optimization, and; 6) reporting [Tabatabaee and Saliminejad, 2009].

Ghasemzadeh Tehrani [Ghasemzadeh Tehrani, 2004] developed a pavement management system as a study for rural roads of Khorasan Province at Shahrood University. He produced software with the capability of maintenance and repair planning and presentation after data analysis [Ghasemzadeh Tehrani, 2004].

Saffarzadeh et al. [Saffarzadeh et al., 2006] used the Analytical Hierarchy Process (AHP) method and developed a multi-criteria model for pavement management system at the project level. This model considers various components including economic, environmental and social factors. In their research, the process of prioritizing the options and pavement management decisions have been improved by using life cycle costs analysis and a hierarchical analysis process. The most effective parameters for selecting the method of M&R are the economic factor, riding quality, drainage quality and structural strength [Saffarzadeh et al., 2006].

A system was developed in Isfahan as a joint project between the university and executive systems [Behbahani, 2004]. Urban streets management system was developed in Isfahan by the research section of Isfahan University of Technology in cooperation with Isfahan municipality in 1980. These studies were according to AASHTO standards and the Isfahan climate. The Isfahan management system claimed to be the first experience in the urban pavement management system in Iran [Behbahani, 2004].

Despite these efforts, there is no union and comprehensive system for the practical part of the country yet. This lack of structure is obvious in funds allocation. The country’s management decisions in the field of pavement are mostly uneconomical and there aren’t any scientific and technical analyzes [Saffarzadeh et al., 2006].

The importance of a modern and efficient pavement management system is evident, especially, for countries like Iran, where most trips are done through road transportation networks [Goli et al., 2016].

Some researches into pavement management systems have been undertaken in Iran in some studies. However, there is no connection between these systems and may not be practical at this point in time [Saffarzadeh et al., 2006; Shafabakhsh et al., 2008].

Tehran, with an area of 700 square kilometers, has approximately 200 kilometers of streets, the construction of which has burdened the city with huge costs. Maintenance of these passages and keeping them at an ideal level of service is of crucial importance. Therefore, using a system developed specifically for the streets of Tehran could satisfy these requirements. Tehran’s various conditions must be considered for developing a special performance prediction model. Collecting and recording pavement distresses data is an important subject. Unfortunately, the existing system isn’t working properly in this case and there isn’t enough available data. The model with more prediction accuracy and fewer data requirements is the best choice for Tehran. These conditions exist in deterministic models like HDM-4 and PHT. The model used for this study is a deterministic model based on the PHT model structure. PHT is a modern model with a structure similar to HDM and data requirements less than HDM. In this study, the PHT model is utilized. For this purpose, major pavement distresses were considered in this model and less important distresses were not included. Part of the PHT model equations will change after calibration and new and independent equations can be created for Tehran. PHT model was preferred for Tehran, because of fewer data requirements and more prediction accuracy. The less input data requirement is an important factor [FHWA, 2013]. Furthermore, Iran is not well-positioned in terms of the quality of pavement condition databases. The PHT model has three calibration levels. As future prospects, higher calibration levels can be used if there is more data. Model details will be introduced in the following sections.

3. System Database

Iran has a fairly poor condition in terms of the database in pavement management. No proper and complete information is available, because there isn’t any regular annual collecting system in Iran. Therefore, we select a model that requires fewer input data and will be applicable to Tehran. However, this model with fewer data requirements has acceptable accuracy and is the best choice for Tehran. The required data included four kinds of distresses and some laboratory, environmental and traffic information. Distress data included crocodile cracks, transverse cracks, rutting, and roughness. Also, we need simple environmental and traffic data that are easily available. Required laboratory data in this model are recorded during pavement construction.

We need data collection for two different periods of time, for an acceptable level of calibration. This model does not need data for several consecutive years and/or data for more than two periods of time. The database should be numerical and easily usable. In the case of pictorial data collection, they should be converted into numerical values. Numerical data collection is better than the pictorial collection; because pictures have not enough accuracy.

3.1 International Roughness Index (IRI)

Many user surveys, on both national and local levels, have shown us that pavement smoothness is one of the main factors when it comes to rating the nation’s highways. The IRI is a profile-based roughness statistic that has become a standard indicator of road roughness in the United States and elsewhere around the world. The research foundation for the IRI occurred under an NCHRP project in the late 1970s, described in NCHRP Report 228 [Gillespie et al., 1980]. In the interest of encouraging the use of a common roughness measure in all significant projects throughout the world, an International Roughness Index (IRI) has been selected. The IRI is a standardized roughness measurement related to those obtained by response-type road roughness measurement systems (RTRRMs), with the recommended unit: meters per kilometer (m/km) [Goli et al., 2018]. Technically, the IRI is a mathematical representation of the accumulated suspension stroke of a vehicle, divided by the distance traveled by the vehicle during a test. Thus, it has units of slope. Instead of accumulating the suspension stroke with a test vehicle, the IRI is calculated from a measured longitudinal road profile using a quarter-car simulation [Kavussi et al., 2016]. Because of the importance of ride quality, IRI is one of the main indicators to evaluate pavement performance. In this study, IRI was used as the main distress index of the model.

4. Model

4.1 Sub-models

Model initial relationships are shown in the following. The calibration coefficients are not determined in these relationships. It is necessary to perform calibration operations. Prediction models for fatigue cracking (in sort of crocodile cracks), rutting, transverse cracking, and roughness are the commonly used models in order to assess the performance of the pavements [Butt et al., 1987]. These models are discussed below.

- **Crocodile crack prediction model**

This sub-model predicts the percent of crocodile crack on the segment. The prediction is based on traffic and laboratory variables [FHWA, 2013]:

$$ACRK = \frac{89.644}{0.1331 + C_0 \sum_{n=1}^{n=k} FDAM^{C_1}} \qquad (1)$$

$$FDAM = {}^{MESAL}/_{N_f} \qquad (2)$$

ACRK: Crocodile crack (area percent)

MESAL: Total 18-kip ESALs for each given month

N_f: Allowable number of 18-kip ESALs applications

C_0, C_1: Calibration coefficients

- **Rutting prediction model**

This sub-model predicts the mean depth of rutting on the segment. The prediction is based on traffic, environmental and laboratory variables. The most effective factors on this distress are mean annual air temperature, vertical strain in the middle of the base layer, mean annual precipitation or rainfall, subgrade resilient modulus at optimum moisture content and traffic volume [FHWA, 2013].

$$\mathrm{TRUT} = \mathrm{ACRUT} + \mathrm{BASERUT} + \mathrm{SUBGRUT} \qquad (3)$$

$$\mathrm{ACRUT} = \mathrm{C}_2 * \mathrm{MAAT}^{1.5606} * \sum_{\mathrm{n}=1}^{\mathrm{k}} (\varepsilon_{\mathrm{vHMA}} * \mathrm{MESAL}^{0.4791}) \qquad (4)$$

$$BASERUT = C_3 * \varepsilon_{vBASE} * h_B * CESAL^{0.1307} \qquad (5)$$

$$\mathrm{SUBGRUT} = (\mathrm{C}_4\mathrm{PRECIP} + \mathrm{C}_5\mathrm{FI}) \left(\frac{\varepsilon_0}{\varepsilon_\mathrm{R}}\right)^{0.9692} * \mathrm{e}^{-\left(\frac{\rho}{\mathrm{CESAL}}\right)^{\beta}} * (\varepsilon_{\mathrm{vSUBG}})^{0.1116} \qquad (6)$$

TRUT: Total pavement rutting (in)

ACRUT: HMA layer rutting (in)

BASERUT: Base layer rutting (in)

SUBGRUT: Subgrade layer rutting (in)

MAAT: Mean annual air temperature (°F)

CESAL: Cumulative 18-kip ESALs since last improvement or original construction

PRECIP: Mean annual precipitation/rainfall (in)

C_2, C_3, C_4, C_5: Calibration coefficients

- **Transverse crack prediction model**

This sub-model predicts the percent of transverse crack on the segment. The prediction is based on environmental and laboratory variables. The most effective factors on this distress are mean annual air temperature and HMA binder content by volume [FHWA, 2013]:

$$\mathrm{TCRK} = \left(\frac{\mathrm{AGE}}{\mathrm{AGE}+1}\right)\left(\frac{6000}{1+C_6{}^{(C_7\mathrm{AGE}+\mathrm{FACTOR})}}\right) \quad (7)$$

$$\mathrm{FACTOR} = 1472.2 + 3.167H_{\mathrm{HMA}} - 879.8\log\log\eta - 16.98\mathrm{Va} - 3.385\mathrm{PCT}3/4 - 0.25\mathrm{FCTYC} \quad (8)$$

TCRK: The transverse cracks per mile (ft/mile)

C_6, C_7: Calibration coefficients

AGE: Pavement age (years)

H_{HMA}: HMA thickness (in)

Va: HMA mix air void content (percent)

PCT34: Cumulative percent retained on the ¾ in sieve for the HMA

FTCYC: Mean annual air freeze-thaw cycles

- **Roughness prediction model**

This sub-model predicts the mean value of the International Roughness Index on the segment. The prediction is based on traffic, environmental and laboratory variables. The most effective factors on this distress are mean annual air temperature, strain at the bottom of the HMA layer, HMA mix as-constructed air voids, HMA mix effective as-constructed placed volumetric binder content, traffic volume, vertical strain in the middle of the base layer, mean annual precipitation or rainfall, subgrade resilient modulus at optimum moisture content, and HMA binder content by volume [FHWA, 2013].

$$\mathrm{IRI} = \mathrm{INI}_{\mathrm{IRI}} + C_8 * \mathrm{TRUT} + C_9 * \mathrm{ACRK} + C_{10} * \mathrm{TCRK} + C_{11} * \mathrm{SF} \quad (9)$$

INI_{IRI}: IRI initial value

TRUT: Total pavement rutting (in)

SF: Parameter influencing on roughness related to subgrade

IRI: International Roughness Index (in/mile)

C_8, C_9, C_{10}, C_{11}: Calibration coefficients

4.2 Calibration and Validation

This model has three calibration levels. These levels must be selected according to available data and conditions. Level 3 of calibration is the highest level and is not usable in Tehran at the present time due to the quality of data available. The level 3 calibration may be able to be used in Tehran after the appropriate data has been collected. This could be done in one year given the appropriate support. In this study, level 2 calibration was used.

Six data sets were used for Tehran model calibration and validation. The calibration data includes set1 (a segment of Tehran – Saveh freeway in the south of Tehran province), set2 (a segment of Saveh – Tehran freeway in the south of Tehran province), set3 (a segment of Bagheri highway in the north direction in east of Tehran), set4 (a segment of Bagheri highway in south direction in the east of Tehran). The validation data includes set5 (a segment of Ab'ali – Roodehen road in the northeast of Tehran province), set6 (a segment of Roodehen – Ab'ali road in the northeast of Tehran province). The calibration coefficients changed in a way that the difference between the results of the model and the collected value was a minimum.

The required data was obtained from two organizations: Iran's Ministry of Roads and Urban Development, and Tehran Municipality. This was including summary of traffic information, temperature and precipitation and freezing index, underground water depth, HMA mix air void content, HMA mix bitumen content, subgrade soil plasticity index, HMA dynamic modulus and thickness, amount of fine sand particles in subgrade, amount of silt particles in subgrade, base layer thickness, amount of clay size particles in subgrade, subgrade resilient modulus, percent passing ¾ in sieve for the HMA mix, tensile strain at the bottom of the HMA layer, vertical strain in three layers, initial IRI, initial crocodile crack, initial rutting, and initial transverse cracking [FHWA, 2013].

Mean Relative Representational Error (MRRE) was used for the calibration coefficient test. A loop was created in MATLAB software to test all the logical states of the calibration coefficients. There are more than 1000 modes for each sub-model. For each mode, the predicted value was calculated. Then, the MRRE value was calculated by using predicted and actual distresses values.

$$\mathrm{MRRE} = \left(\frac{\mathrm{Y_{actual}} - \mathrm{Y_{predicted}}}{\mathrm{Yactual}} * 100\right) \qquad (10)$$

The minimum values of MRRE were chosen as the best results over calibration operations. Calibration coefficients were obtained based on it. More details including the results are presented in Table 1. The flowchart of each sub-model, all the inputs, all the variables, the measured values of each sub-model, as well as the results of a numerical method for statistical analysis of the obtained coefficients are provided in the appendix.

Table 1. MRRE test for Tehran pavement prediction model and calibration coefficients

	ACRK (Crocodile crack)					
Sub-model coefficient:	($C_0 = 7.595$		,		$C_1 = 0.78$)	
	Calibration sites				Validation sites	
	Site1	Site2	Site3	Site4	Site5	Site6
Actual value:	3.75	3.375	2.51	2.86	3.02	3.17
Model prediction:	3.747	3.366	2.482	2.853	3.011	3.155
MRRE:	0.08	0.267	1.12	0.245	0.298	0.473
	TRUT (Rutting)					

Sub-model coefficient:	**($C_2 = 0.000328$, $C_3 = 4.71$, $C_4 = 0.00215$, $C_5 = 0.0000838$)**					
	Calibration sites				**Validation sites**	
	Site1	**Site2**	**Site3**	**Site4**	**Site5**	**Site6**
Actual value:	**2.183**	**2.167**	**1.95**	**1.97**	**2.11**	**2.175**
Model prediction:	**2.1838**	**2.1667**	**1.947**	**1.963**	**2.103**	**2.169**
MRRE	**0.037**	**0.014**	**0.154**	**0.355**	**0.332**	**0.276**

TCRK (Transverse crack)

Sub-model coefficient:	**($C_6 = 1.02$, $C_7 = 5.0989$)**					
	Calibration sites				**Validation sites**	
	Site1	**Site2**	**Site3**	**Site4**	**Site5**	**Site6**
Actual value:	**32**	**29.2**	**33.8**	**41.3**	**43.2**	**47.7**
Model prediction:	**32.5**	**30**	**34.1**	**42.4**	**43.7**	**47.8**
MRRE	**1.56**	**2.74**	**0.887**	**2.66**	**1.157**	**0.21**

IRI (Roughness)

Sub-model coefficient:	**($C_8 = 65$, $C_9 = 0.56$, $C_{10} = 0.017$, $C_{11} = 0.028$)**					
	Calibration sites				**Validation sites**	
	Site1	**Site2**	**Site3**	**Site4**	**Site5**	**Site6**
	3.515	**3.392**	**3.050**	**3.2**	**3.081**	**3.41**
Actual value:	**3.519**	**3.398**	**3.057**	**3.204**	**3.089**	**3.412**
Model prediction:	**0.114**	**0.177**	**0.229**	**0.125**	**0.259**	**0.059**
MRRE						

5. Model Software and Outputs

MATLAB was used for programming this model. The graphical environment has been created for this model by some changes in MATLAB. This model's software is completely independent and executable on every system. This software contains 35 inputs that will be asked for by the software. These inputs were shown in Figure 1. They were divided into several groups, shown in Figure 1 as the software input window.

Figure 1. Software input window

The variables are described in the following:

- **AGE**: Pavement age in years
- **V_a**: Asphalt mixtures air void content, percent
- **V_b**: Asphalt mixtures bitumen content, percent by volume
- **PI**: Subgrade soil plasticity index
- **E**: Asphalt mixtures dynamic modulus, MPa
- **hAC**: Asphalt mixtures thickness, cm
- **FSAND**: Amount of fine sand particles in subgrade, percent
- **SILT**: Amount of silt particles in subgrade, percent
- **hB**: Base layer thickness, cm
- **CLAY**: Amount of clay size particles in subgrade, percent
- **Mr**: Subgrade resilient modulus, MPa
- **PCT3/4**: Percent passing ¾ in the sieve for the asphalt mixtures mix
- **A**: Regression intercept of viscosity-temperature susceptibility
- **VTS**: Regression slope of viscosity-temperature susceptibility
- **EPSILONT**: tensile strain at the bottom of the asphalt mixtures layer
- **epsilonvSUBG**: Vertical strain in the top of the subgrade
- **epsilonvBASE**: Vertical strain in the middle of the base layer
- **epsilonvHMA**: Vertical strain in the middle of the asphalt mixtures layer
- **GR**: Annual Average Daily Traffic (AADT) growth rate
- **PCV**: Number of passing vehicles
- **HVV**: Number of passing heavy vehicles
- **RRV**: Number of passing recreational vehicles
- **DD**: Directional distribution coefficient
- **MAAT**: Mean annual air temperature, ℃
- **GWT**: Depth to the groundwater table, m
- **PRECIP**: Mean annual precipitation or rainfall, mm
- **FI**: Mean annual freezing index, (℃ - day)
- **FCTYC**: Mean annual air freeze-thaw cycles
- **INIIRI**: Initial IRI, (in/mi)
- **INIACRK**: Initial crocodile crack, percent
- **INITRUT**: Initial rutting, in
- **INITCRK**: Initial transverse cracking, (ft/mile)

Software output consists of two parts. The first part consists of four diagrams. These diagrams show roughness, crocodile crack, rutting, and transverse crack progression over time. Also, threshold values and the time to reach these values are shown. Output diagrams related to a set of experimental data are shown in the following.

The second part of the outputs contains two values that represent pavement remaining service life. These are the RSL_normal parameters and RSL_min parameters. These measures provide the following information:

- **[RSL _ normal] parameter**

This parameter represents pavement remaining service life with model weighting coefficients. In this case, the IRI parameter considered as the most influential factor and the transverse crack considered as the least influential factor. This value represents the logical and main results of the model.

- **[RSL _ min] parameter**

This parameter calculates pavement remaining service life by checking the four distresses and time to reach this value to the threshold. In fact, this amount is very conservative.

To display the output sample based on the calibrated model, a sample of Tehran – Saveh freeway data (set1) was used as the input variable. Pavement distresses prediction was obtained as shown in Figure 2.

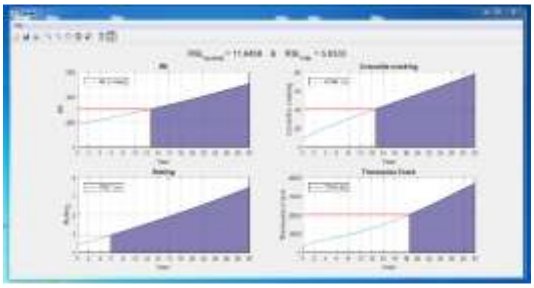

Figure 2. Model output sample for set1 test area

Figure 2 shows that the pavement has a critical condition in rutting after 5 years. Other measures have good conditions over the next 10 years and don’t need any operation. Also, checking the pavement condition is required after 11 years.

6. Conclusions

Today, most authorities pay special attention to the maintenance of roads and protecting the huge investment that has gone into it. If neglected, it will impose prohibitive costs on road agencies. Given budget constraints, finding low-cost but highly efficient maintenance methods has gained importance, which gives rise to discussions about preventive measures and precise prioritization of maintenance operations. Tehran, with a huge amount of traffic and streets, needs a management system based on economic and preventive operations. Therefore, in this study, a model was presented for Tehran based on preventive actions.

This model with high prediction accuracy and fewer data requirements is very suitable for Tehran. Budgeting will be organized by this model and operations will be classified according to execution type and time with a huge reduction in costs. The model’s software is completely independent and executable on every system. It has a graphical environment and is easy to use.

As a proposal for the future, we can use the highest level of calibration based on long-term planning. For this purpose, operations and data required will be specified and collected for 4 to 5 years, continuously. After this period, the highest level of calibration can be applied for Tehran by using these yearly data. Therefore, we would develop a model more accurate and more specific than this study’s model.

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Appendix: Details of Developed Sub-Models

The flowchart of each sub-model, all the utilized inputs, all the equations, typical values of the measured parameters for each sub-model, and the results of a numerical method to find the unknown coefficients are provided in this section. The numerical procedures were based on trial and error method and the Root Mean Square Error (RMSE) was calculated for each case. Furthermore, the measured values for each sub-model were determined for every 50 m of each site and the average values were entered into the calculations. Totally, 6 sites were considered: Site 1) Tehran-Saveh; Site 2) Saveh-Tehran; Site 3) Bagheri (South-North); Site 4) Bagheri (North-South); Site 5) Ab’ali-Roodehen; and Site 6) Roodehen-Ab’ali.

It is worth mentioning that the traffic data are not included in this appendix. For more information refer to “Bagherian, P., Investigating of pavement remaining service life prediction models and suggesting an applicable model for Tehran (M.Sc. Thesis), School of Civil Engineering, College of Engineering, University of Tehran, 2017”.

A- ACRK Model

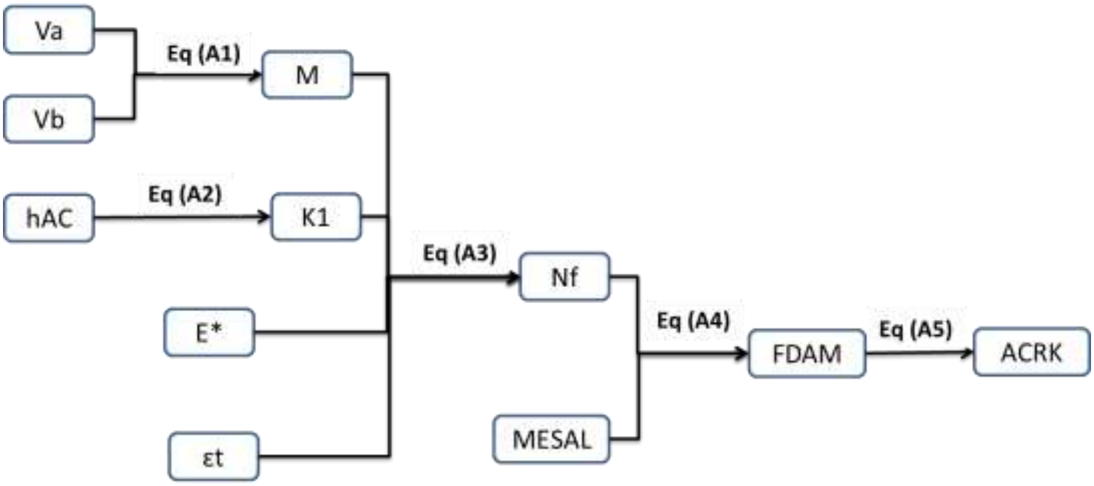

Figure A-1 Flowchart of determining the coefficients of ACRK model

Table A-1 Input parameters of ACRK model

Parameter	**Site 1**	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**
Va	5	5	5.5	5.5	5.3	5.3
Vb	9.5	9.5	9.8	9.8	10	10
hAC	16	16	16	16	18	18
E*	200000	200000	210000	210000	220000	220000
εt	0.00028	0.00028	0.00023	0.00023	0.0002	0.0002

Va: Air void (%)
Vb: Binder content (%)
hAC: Surface layer thickness (cm)
E*: Dynamic Modulus (psi)
εt: Tensile strain at the bottom of the surface layer

$$M = 4.84\left(\frac{V_a}{V_a + V_b} - 0.69\right) \tag{A1}$$

$$K_1 = \frac{1}{0.000398 + \frac{0.003602}{1 + e^{(11.02 - 3.49 h_{AC})}}} \tag{A2}$$

$$N_f = 1.2347 \times 0.00432 \times K_1 \times 10^M \times \left(\frac{1}{E^*}\right)^{1.537} \times \left(\frac{1}{\varepsilon_t}\right)^{4.215} \tag{A3}$$

$$FDAM = \frac{MESAL}{N_f} \tag{A4}$$

$$ACRK = \frac{89.644}{0.1331 + C_0 \sum_{n=1}^{n=k} FDAM^{C_1}} \tag{A5}$$

Table A-2 Typical Crack percentage for different sections of Site 3 (Average ACRK=2.51)

Section	Start (m)	End (m)	Crack percentage
1	0	50	1.1
2	50	100	2.0
3	100	150	1.5
4	150	200	5.3
5	200	250	4.3
6	250	300	2.8
7	300	350	2.2
8	350	400	0.0
9	400	450	6.6
10	450	500	2.2
11	500	550	2.2
12	550	600	0.0
Average			2.51

Table A-3 Summary of measured values for ACRK

Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
3.75	**3.374**	**2.51**	**2.86**	**3.02**	**3.17**

Table A-4 Determining the coefficients of ACRK model based on a numerical method

Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	C0	C1	RMSE
3.762	3.393	2.533	2.88	3.241	3.259	7.56	-0.77	0.0696
3.762	3.397	2.549	2.901	3.244	3.266	7.565	-0.772	0.0726
3.766	3.402	2.552	2.904	3.27	3.285	7.572	-0.774	0.0819
3.783	3.398	2.54	2.892	3.23	3.241	7.578	-0.778	0.0663
3.761	3.387	2.531	2.872	3.1	3.213	7.585	-0.772	0.0276
3.758	3.381	2.519	2.866	3.035	3.192	7.591	-0.775	0.0188
3.748	**3.366**	**2.482**	**2.853**	**3.011**	**3.155**	**7.595**	**-0.78**	**0.0100**
3.745	3.358	2.466	2.847	2.998	3.119	7.598	-0.782	0.0214
3.738	3.355	2.451	2.844	2.985	3.096	7.602	-0.77	0.0302

3.734	3.35	2.444	2.832	2.965	3.045	7.605	-0.773	0.0453
3.735	3.352	2.449	2.836	2.969	3.052	7.608	-0.775	0.0424
3.732	3.344	2.438	2.829	2.652	3.011	7.611	-0.77	0.1183
3.75	**3.374**	**2.51**	**2.86**	**3.02**	**3.17**	**Measured values of ACRK**		

B- TRUT Model

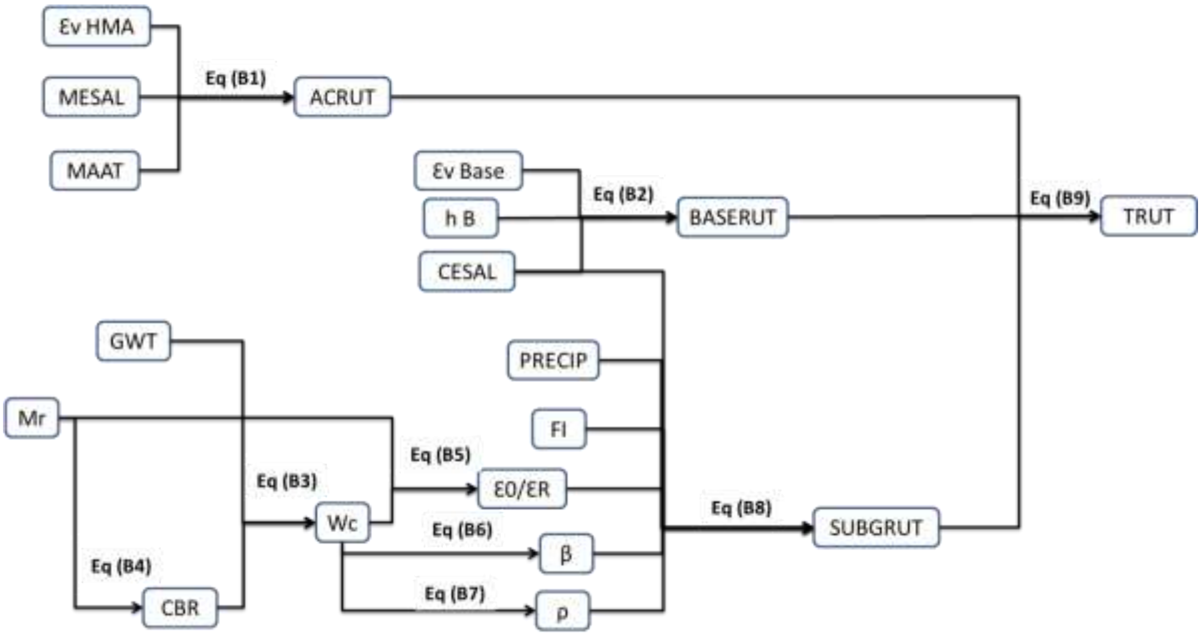

Figure B-1 Flowchart of determining the coefficients of TRUT model

Table B-1 Input parameters of TRUT model

Parameter	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
Mr	20000	20000	22000	22000	20000	20000
εv HMA	0.00023	0.00023	0.00021	0.00021	0.00020	0.00020
εv Base	0.00094	0.00094	0.00098	0.00098	0.00010	0.00010
εv Subgrade	0.00035	0.00035	0.00053	0.00053	0.00048	0.00048
h B	15	15	14	14	16	16
MAAT	63.9	63.9	65.26	65.26	49.50	49.50
PRECIP	5.65	5.65	5.54	5.54	6.48	6.48
FI	15	15	11	11	39	39

GWT (ft)	65.5	65.5	105	105	52.5	52.5

Mr: Resilient Modulus (psi)
εv HMA: Vertical strain at the middle of HMA
εv Base: Vertical strain at the middle of the base
εv Subgrade: Vertical strain at the middle of subgrade
h B: Base thickness (cm)
MAAT: Mean annual air temperature (°F)
PRECIP: Mean annual precipitation/rainfall (in)
FI: Average daily freezing index (day-°F)
GWT: Groundwater table depth (ft)

$$ACRUT = C_2 \times MAAT^{1.5606} \times \sum_{n=1}^{k} \left(\varepsilon_{vHMA} \times MESAL^{0.4791} \right) \tag{B1}$$

$$BASERUT = C_3 \times \varepsilon_{vBase} \times h_B \times CESAL^{0.1307} \tag{B2}$$

$$W_c = 51.712 \times (CBR)^{-0.3586 GWT^{0.1192}} \tag{B3}$$

$$CBR = \left(\frac{M_r}{2555} \right)^{1.5625} \tag{B4}$$

$$\left(\frac{\varepsilon_0}{\varepsilon_R} \right) = 10^{(0.74168 + 0.08109 W_c - 0.000012157 M_r)} \tag{B5}$$

$$\beta = 0.7 \times 10^{(-0.61119 - 0.017638 W_c)} \tag{B6}$$

$$\rho = 10^{(0.622685 + 0.541524 W_c)}$$

(B7)

$$SUBGRUT = (C_4 PRECIP + C_5 FI) \left(\frac{\varepsilon_0}{\varepsilon_R} \right)^{0.9692} \times e^{-\left(\frac{\rho}{CESAL} \right)^{\beta}} \times \left(\varepsilon_{vSUBG} \right)^{0.1116} \tag{B8}$$

$$TRUT = ACRUT + BASERUT + SUBGRUT \tag{B9}$$

Table B-2 Typical Rut depth for different sections of Site 4 (Average TRUT=1.97)

Section	Start (m)	End (m)	Rut depth (mm)
1	0	50	2.0
2	50	100	2.0
3	100	150	1.8
4	150	200	1.7

5	200	250	1.9
6	250	300	2.1
7	300	350	1.9
8	350	400	2.2
9	400	450	1.9
10	450	500	2.2
11	500	550	2.0
12	550	600	1.9
Average			1.97

Table B-3 Summary of measured values for TRUT

Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
2.183	**2.167**	**1.95**	**1.97**	**2.11**	**2.175**

Table B-4 Determining the coefficients of TRUT model based on a numerical method

Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	C2	C3	C4	C5	RMSE
2.16	2.08	1.929	1.943	1.99	2.153	0.000318	4.64	0.0022	0.0000845	0.0431
2.166	2.095	1.935	1.955	2.011	2.157	0.000322	4.68	0.00218	0.0000842	0.0351
2.17	2.131	1.94	1.961	2.075	2.165	0.000325	4.70	0.00216	0.000084	0.0151
2.1838	**2.1667**	**1.947**	**1.963**	**2.103**	**2.169**	**0.000328**	**4.71**	**0.00215**	**0.0000838**	**0.0033**
2.186	2.173	1.977	2.02	2.168	2.198	0.00033	4.75	0.00212	0.0000835	0.0235
2.187	2.175	1.984	2.025	2.173	3.02	0.000333	4.78	0.00209	0.0000832	0.2357
2.189	2.1755	1.989	2.029	2.181	3.05	0.000337	4.80	0.00212	0.0000828	0.2443
2.191	2.177	1.992	2.031	2.188	3.11	0.00034	4.84	0.00215	0.0000825	0.2611
2.194	2.18	1.998	2.038	2.195	3.15	0.000344	4.88	0.00218	0.0000821	0.2725
2.184	2.168	1.959	1.982	2.12	2.178	0.00033	4.73	0.00213	0.0000836	0.0051
2.185	2.171	1.961	1.99	2.13	2.187	0.000335	4.75	0.00211	0.0000835	0.0091
2.1857	2.173	1.97	2.01	2.15	2.195	0.000337	4.77	0.0021	0.0000833	0.0176
2.186	2.175	1.98	2.017	2.17	3.01	0.000338	4.77	0.00208	0.0000831	0.2327
2.183	**2.167**	**1.95**	**1.97**	**2.11**	**2.175**	**Measured values of TRUT**				

C- TRCK Model

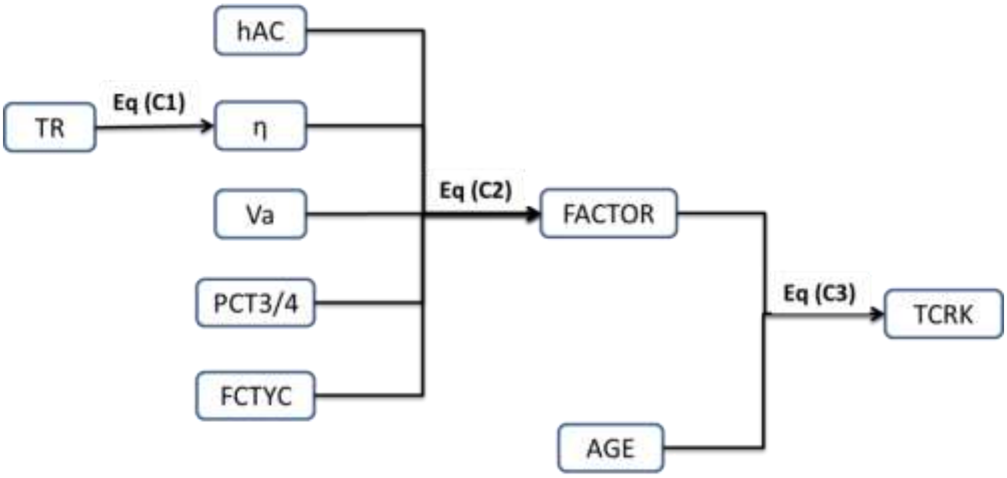

Figure C-1 Flowchart of determining the coefficients of TRUT model

Table C-1 Input parameters of TCRK model

Parameter	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
TR	62.5	62.5	59.5	59.5	50.3	50.3
hAC	16	16	16	16	18	18
Va	5	5	5.5	5.5	5.3	5.3
PCT3/4	5	5	3	3	6	6
FCTYC	60	60	52	52	88	88

TR: Temperature of pavement surface (°F)
hAC: Surface layer thickness (cm)
Va: Air void (%)
PCT3/4: Cumulative percent retained on the ¾ in sieve for the HMA
FCTYC: Mean annual air freeze-thaw cycles

$$\log\log\eta = 11.0134 - 3.6954\log T_R \tag{C1}$$

$$FACTOR = 1472.2 + 3.167h_{AC} - 879.8\log\log\eta - 16.98V_a - 3.385PCT\,3/4 - 0.25FCTYC \tag{C2}$$

$$TCRK = \left(\frac{AGE}{AGE+1}\right)\left(\frac{6000}{1+C_6^{(C_7 AGE + FACTOR)}}\right) \tag{C3}$$

Table C-2 Typical transverse crack length for different sections of Site 5 (Average TCRK=43.2)

Section	Start (m)	End (m)	Crack percentage
1	0	50	0.8
2	50	100	1.1
3	100	150	2.7

4	150	200	3.0
5	200	250	4.5
6	250	300	3.0
7	300	350	0.0
8	350	400	0.0
9	400	450	3.4
10	450	500	4.0
11	500	550	1.4
12	550	600	2.0
Average (per 1 kilometer)			43.2

Table C-3 Summary of measured values for TCRK

Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
32	**29.2**	**33.8**	**41.3**	**43.2**	**47.7**

Table C-4 Determining the coefficients of TCRK model based on a numerical method

Site 1	Site 2	Site 3	Site 4	Site 5	Site 6	C6	C7	RMSE
34.1	31	34.8	43.8	45.5	48.7	1.01	-5.0975	1.3288
34.5	31.2	35.4	44.1	45.8	49.2	1.01	-5.0978	1.5722
32.9	29.9	34.5	43.5	44.8	48.1	1.015	-5.0982	0.8827
33.2	31.1	34.9	43.8	45	48.3	1.015	-5.0985	1.1587
31.5	29.1	33.4	40	42.4	48.3	1.02	-5.0987	0.5091
32.5	**30**	**34.1**	**42.4**	**43.7**	**47.5**	**1.02**	**-5.0989**	**0.4546**
32.8	30.5	34.4	43.5	44.8	47.8	1.02	-5.0993	0.9174
32.7	30.2	34.3	43.2	44.1	48	1.025	-5.0995	0.7217
33.1	30.6	34.6	43.7	44.9	48.9	1.025	-5.0997	1.0763
33.3	31	35	44	45.2	48.2	1.025	-5.0999	1.2217
32.3	30.8	34.9	43.8	45.1	48.5	1.03	-6.0002	1.0939
33.5	31.2	35.3	44.2	45.4	48.8	1.03	-6.0005	1.3832
32	**29.2**	**33.8**	**41.3**	**43.2**	**47.7**	**Measured values of TCRK**		

D- IRI Model

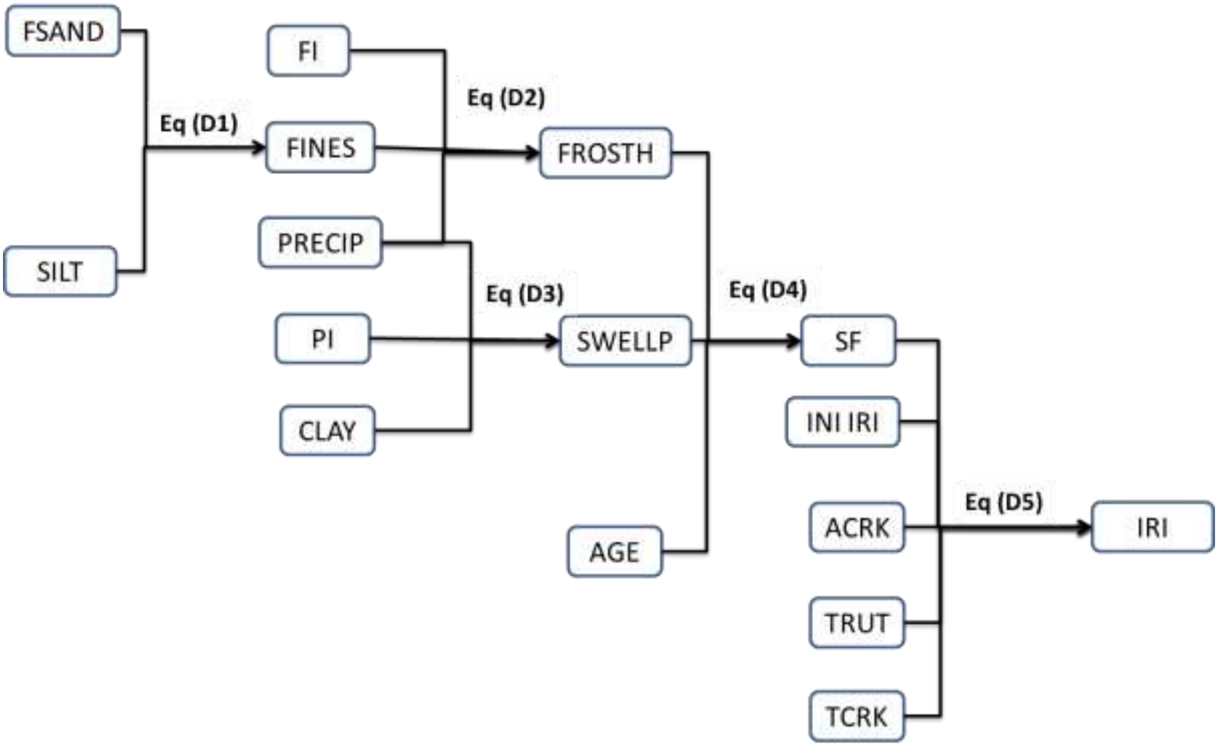

Figure D-1 Flowchart of determining the coefficients of the IRI model

Table D-1 Input parameters of the IRI model

Parameter	Site 1	Site 2	Site 3	Site 4	Site 5	Site 6
FSAND	60.5	60.5	55.3	55.3	58	58
SILT	12.9	12.9	12.7	12.7	11.1	11.1
CLAY	14.1	14.1	13.4	13.4	12.8	12.8
PRECIP	5.65	5.65	5.54	5.54	6.48	6.48
FI	15	15	11	11	39	39
PI	5.8	5.8	5.6	5.6	5.5	5.5
ACRK	3.748	3.366	2.482	2.853	3.011	3.155
TRUT	2.1838	2.1667	1.947	1.963	2.103	2.169
TCRK	32.5	30	34.1	42.4	43.7	47.5
INI IRI	63.4	63.4	63.4	63.4	63.4	63.4

FSAND: Sand percentage in subgrade (particles between 0.074 to 0.42 mm)
SILT: Silt percentage in subgrade (particles between 0.002 to 0.074 mm)
CLAY: Clay percentage in subgrade (particles finer than 0.002 mm)
PRECIP: Mean annual precipitation/rainfall (in)
FI: Average daily freezing index (day-°F)
PI: Plasticity Index

ACRK: Crocodile crack (area percent)
TRUT: Total pavement rutting (in)
TCRK: Transverse cracks per mile (ft/mile)
INI IRI: Default value of MEPDG for Initial IRI (in/mi)

$$FINES = FSAND + SILT \tag{D1}$$

$$FROSTH = \ln\left((PRECIP + 1) \times FINES \times \left(FI + 1\right)\right) \tag{D2}$$

$$SWELLP = \ln((PRECIP + 1) \times CLAY \times (PI + 1)) \tag{D3}$$

$$SF = FROSTH + SWELLP \times AGE^{1.5} \tag{D4}$$

$$IRI = INI_{IRI} + C_8 TRUT + C_9 ACRK + C_{10} TCRK + C_{11} \times SF \tag{D5}$$

Table D-2 Typical IRI vales for different sections of Site 6 (Average IRI=3.41)

Section	**Start (m)**	**End (m)**	**Average IRI**
1	0	50	3.02
2	50	100	1.52
3	100	150	5.22
4	150	200	2.11
5	200	250	3.65
6	250	300	5.33
7	300	350	3.32
8	350	400	0.66
9	400	450	0.53
10	450	500	5.23
11	500	550	4.98
12	550	600	5.43
Average			**3.41**

Table D-3 Summary of measured values for IRI

Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**
3.515	**3.392**	**3.05**	**3.2**	**3.08**	**3.41**

Table D-4 Determining the coefficients of the IRI model based on a numerical method

Site 1	**Site 2**	**Site 3**	**Site 4**	**Site 5**	**Site 6**	**C8**	**C9**	**C10**	**C11**	**RMSE**
3.524	3.397	3.065	3.212	3.089	3.413	63	0.66	0.0175	0.033	0.0063
3.528	3.405	3.071	3.217	3.097	3.418	63	0.69	0.0175	0.032	0.0100

3.533	3.411	3.077	3.224	3.102	3.425	63	0.71	0.018	0.031	0.0138
3.522	3.395	3.057	3.209	3.093	3.415	64	0.62	0.0173	0.026	0.0050
3.528	3.398	3.059	3.217	3.098	3.419	64	0.64	0.0174	0.031	0.0082
3.532	3.401	3.064	3.221	3.101	3.423	64	0.66	0.0175	0.033	0.0106
3.504	3.382	3.044	3.185	3.066	3.390	65	0.51	0.0172	0.022	0.0089
3.502	3.379	3.042	3.177	3.052	3.396	65	0.53	0.017	0.025	0.0119
3.509	3.384	3.047	3.1925	3.071	3.401	65	0.54	0.0172	0.026	0.0050
3.519	**3.398**	**3.057**	**3.204**	**3.089**	**3.412**	**65**	**0.56**	**0.017**	**0.028**	**0.0036**
3.521	3.399	3.066	3.209	3.095	3.415	66	0.46	0.0172	0.021	0.0068
3.523	3.402	3.074	3.215	3.099	3.419	66	0.48	0.017	0.022	0.0099
3.523	3.410	3.080	3.222	3.0105	3.425	66	0.50	0.0168	0.024	0.0223
3.525	3.418	3.088	3.230	3.112	3.434	66	0.52	0.0165	0.026	0.0182
3.515	**3.392**	**3.050**	**3.200**	**3.081**	**3.410**	**Measured values of IRI**				