HIGHWAY DEVELOPMENT AND MANAGEMENT MODEL – 4 (HDM-4) CALIBRATION

(ADDIS ABABA – MODJO TRUNK ROAD CASE)

By

Tewodros Syum

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SCHOOL OF CIVIL AND ENVIRONMENTAL ENGINEERING
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SCHOOL OF GRADUATE STUDIES
ADDIS ABABA UNIVERSITY

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2014

Approved by Board of Examiners

Advisor	Signature	Date
Dr.-Eng. Wubishet Jekale	________________________	__________________
External Examiner	Signature	Date
Dr. Alemayehu Ambo	________________________	__________________
Internal Examiner	Signature	Date
Dr. Bikila Teklu	________________________	__________________
Chairperson	Signature	Date
Dr.Bikila Teklu	________________________	__________________

Abstract

The Highway Development and Management Tools collectively referred to as HDM-4, developed by the World Bank, incorporates various applications. Some of the are: road performance prediction, road treatment programming, funding estimates, budget allocation, project appraisal, policy impact studies, and a wide range of special applications.

This model is universally applicable given calibrated and has been adopted by many countries in the tropic and all over the world. This unanimous adoptability is true through, local adjustment as per the prevailing condition of the location or the country at which it is going to be used.

Our country, Ethiopia, as one of the countries using this software for project level analysis and especially for economic feasibility analyses, it is noteworthy to know how dependable the software outputs are. In addition, rather than adopting default values, there were no properly documented calibration and validation of the software for Ethiopia so far. These reasons derive and motivate this research to be conducted.

This study is focused on four Road Deterioration and Work Effects (RDWE) models calibrations, namely; roughness – age – environment factor (K_{gm}), crack initiation factor (K_{cia}), crack progression factor ($K_{cp)}$, and general roughness progression factor (K_{gp}).

This paper confirmed that there is discrepancy between the actual observed pavement distress values and the model predictions which indicate the need for calibration. Then, according to HDM-4's calibration techniques, the result showed that the magnitude of roughness increment observed is lower than the default HDM-4's prediction (1.00 for each factors), with K_{gm}=**0.85**. Also, the pavement cracks initiate earlier and progress faster than the one estimated by non – calibrated HDM-4 models, K_{cia}=**0.67** & K_{gp}=**1.49**. Moreover, the general roughness progression adjustment factor turns out to be approximately a unit (K_{gp}**=1.03**) indicating no need of executing it if the other parameters are already adjusted. This mans, project costs estimated by non-calibrated software are generally over estimated by the environmental effects but the other three models of crack and general roughness under estimate project costs.

Acknowledgement

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List of Symbols

AASHTO	American Association of State Highway and Transportation Officials
ERA	Ethiopian Roads Authority
ESAL	Equivalent Standard Axle load
HCM	Highway Capacity Model
HDM-4	Highway Development and Management Tool version 4
	Roughness – age – environment factor
	Crack initiation adjustment factor
K_{cp}	Crack progression adjustment factor
	General roughness progression factor
LTRP	Long Term Rolling Program report
LTPP	Long Term Pavement Performance recording sections
PMS	Pavement Management Systems
	Environment coefficient
MF	Multi – function models
RUE	Road User Effects
RDWE	Road Deterioration and Work Effects
SNP	adjusted structural number of the pavement
SNBASU	contribution of surfacing and base layers
SNSUBA	adjusted structural number of the pavement contribution by the sub-base
SNSUBG	adjusted structural number of the pavement contribution by the subgrade
ΔR increment	Change in roughness due to environment in 1 – year analysis time
	Roughness at the beginning of year t

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1. Introduction

1.1 General

The Highway Development and Management Model-4, (HDM-4), has become widely used as a planning and programming tool for highway expenditures and maintenance standards.

HDM-4 is a computer model that simulates physical and economic conditions over the period of analysis, usually a life cycle, for a series of alternatives and scenarios specified by the user. HDM-4 is designed to make comparative cost estimates and economic evaluations for different construction and maintenance options, including different time-staging alternatives, either for a given road project on a specific alignment or for groups of links on an entire network. It estimates the total costs for a large number of alternative project designs and maintenance alternatives year by year. It presents results discounting the future costs, based on the minimum internal rate of return (MIRR), if desired at different postulated discount rates so that the user can search for the alternative with the lowest discounted total cost.

Three interacting sets of costs (related to construction, maintenance and road use) are added together over time in discounted present values, where the costs are determined by first predicting physical quantities of resource consumption and then multiplying these by unit costs or prices.

As illustrated in Figure 1.1, HDM-4 consists of a series of sub-models that address different aspects of the analysis. Each of these sub-models requires certain input data and each produces its own output. In order to apply the model correctly, one needs to ensure that HDM-4 is given the appropriate input data and has been suitably calibrated. (Bennett & Paterson, 2000)

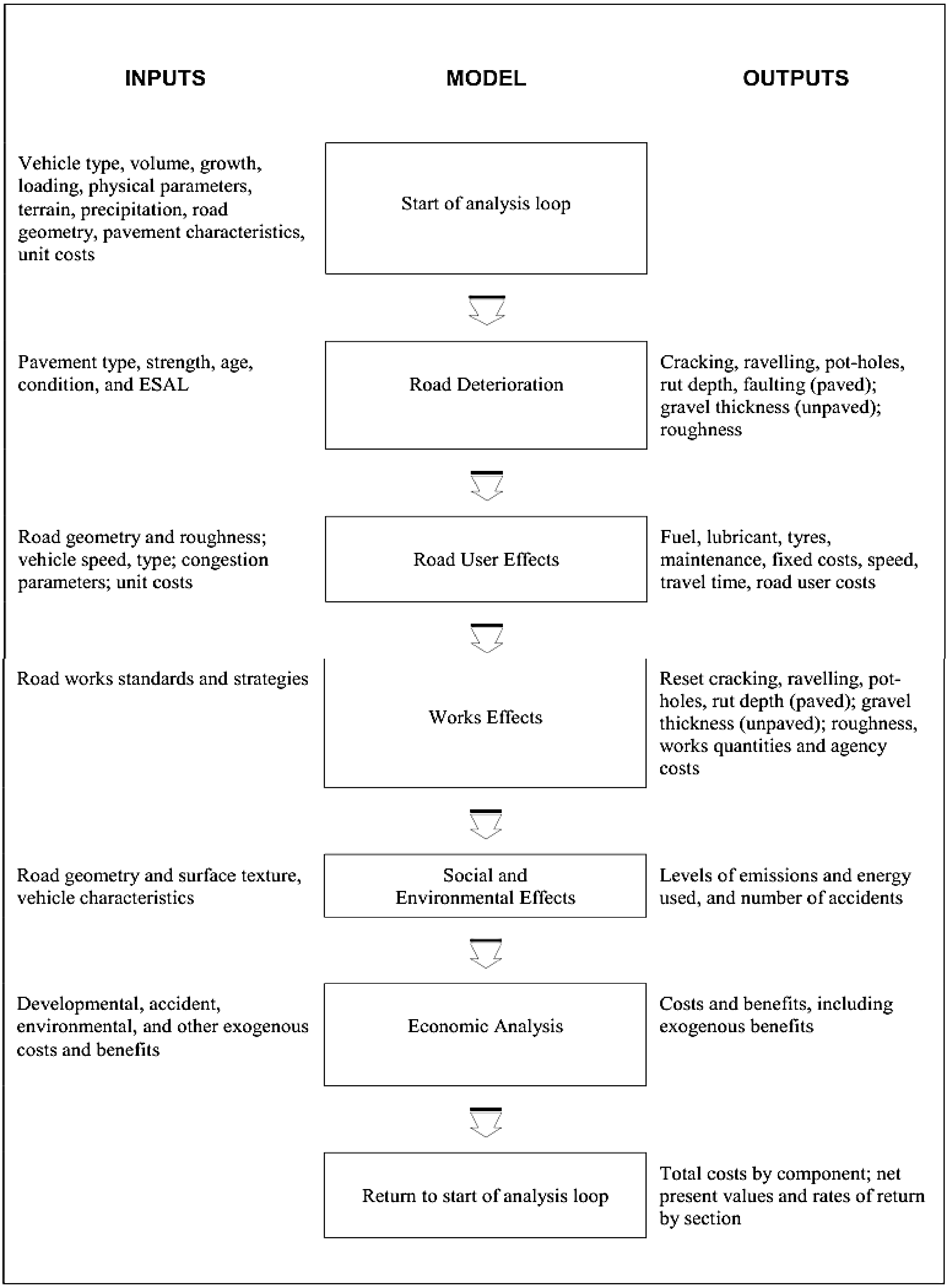

Figure 1.1: Structure of The HDM-4 Model (Source: Bennett & Paterson, 2000)

1.2 Research Background

The Highway Development and Management-4 (HDM-4) model is universally applicable with calibration as required; and it has been adopted by many countries in the tropic (Chai et.al, 2004). Prior to full development and adoption of the software, 36 calibration sections have been set up in 1993 so as to ensure local accuracy (Rohde et al, 1993). The validity of the vehicle speed and operating costs models was built up from four major field studies conducted in Kenya, the Caribbean, Brazil and India (Chesher and Harrison, 1987; Watanatada et al., 1987). The validity of the various road deterioration models was demonstrated on independent field data from up to eight different countries and states in climates ranging from hot arid to cold wet (Paterson, 1987).

HDM-4 models a road network over its life time period whether it is not constructed yet or for the one already in service. The software's models in general can be grouped in to two categories, models for Road User Effects (RUE) and the other for Road Deterioration and Work Effects (RDWE). HDM-4 first predicts the physical condition and quantities of construction/maintenance resource consumption and road user costs. Then it predicts total cost by multiplying resource consumption with their unit cost and by adding road user costs. The model simulates physical and economic conditions over the period of analysis and the results are presented in the Long Term Rolling Program (LTRP) report. The essential part of the LTRP includes the forecasted budget allocation. However, adequate and accurate budget allocation would require the HDM-4 model to generate good prediction of the actual pavement deterioration behavior. These predictions are dependent on input data quality and the accuracy of the models to model the real phenomenon.

Accordingly, the accuracy of the model to represent the real phenomenon depends on the calibration effort applied. Therefore, through calibration procedure the software models are fine-tuned and adjusted so that their simulation resembles the real road condition observed in question.

1.3 Research Problem Statement

As mentioned in research background, HDM-4's universal applicability is made true by assuring that it gives reasonably correct results in selected representative countries around the world. This is more supported by making regional calibration as per the prevailing condition of the location at which it is going to be applied.

Local adaptation and calibration of HDM-4 models can be started by specifying default data sets that represent pavement performance and vehicle resource consumption in the country where the model is being used. Then, by analyzing and comparing the model predictions with respect to actual record data, the model will be more fine-tuned and adjusted more.

Moreover, the need for model calibration to local condition is essential component of the pavement management process. This is because Road Deterioration and Road Work Effects (RDWE) models control the processes of initiation and progression of pavement distress. In return, these outputs have direct influence on economic evaluation of the road network being analyzed, like current or future maintenance budget allocation, maintenance programming, and strategic planning.

Our country, Ethiopia, as one of the countries using the software, need to calibrate the software for reliable results. The calibration can be done for model parameters of Road User Effect (RUE) and/or Road Deterioration and Work Effects (RDWE). However, until now there were no coherent job and documentation over the issue. Rather, there is a general tendency to adopt default software values so far. This problem has been the major motivation to conduct this research.

1.4 Research Questions

1. Does the HDM – 4 software require calibration with respect to Road Deterioration and Road Work Effect (RDWE) models for bituminous paved road (for the case of Addis Ababa – Modjo link)?
2. If “Yes” is the answer, what shall be the calibration factors?
    - Null – Hypothesis: HDM-4 roughness model needs no calibration;
    - Alternative – Hypothesis: HDM-4 roughness model needs calibration.

1.5 Research Objective

General Objective

The main objective of this study is to calibrate HDM-4 model for some of Road Deterioration and Road Work Effects, (RDWE) models. The location selected for calibration analysis is Addis – Mojo link due to better pavement performance recorded data.

According to HDM – 4 guide for calibration and adaptation volume 5, Road Performance and Works Effect models, which model the processes of initiation and progression of pavement distress, along with the level of calibration they require are given in Table – 1, but not more than level 2.

Research Specific Objective

The research specific objectives are:

- To perform first level calibration for Roughness – Age – Environment, Crack Initiation, and Crack Progression; and
- To perform second level calibration of HDM-4 Program for Roughness – Age – Environment, Crack Initiation, and Crack Progression for the case of Addis – Mojo road section.

HDM-4’s main input parameters are shown in Table – 1. Most the parameters given require first level calibration and they should be specified for the project being analyzed.

Table 1.1: HDM-4 Data And RDWE Model Parameters And Calibration Levels Required (Source: Bennett & Paterson, 2000)

Description	**Units**	**Calibration level where local values should be established in place of defaults**		
		Level 1	Level 2	Level 3
Altitude	m	●		
Area Potholed	%	●		
Area with all cracking	%	●		
Area with wide cracking	%	●		
Average rainfall	m/month	●		
Base type		●		
Benkelman beam deflection	mm	●		
Carriageway width	m	●		
Construction age	yr	●		
Effective number of lanes		●		
Horizontal curvature	deg/km	●		
Mean rut depth	Mm	●		
Number of surface layers		●		
Posted speed limit		●		
Preventive treatment age	yr	●		
Rise plus fall	m/m	●		
Roughness	IRI	●		
Roughness age term		●		
Raveling initiation		●	●	
Raveling progression		●	●	
Raveling retardation factor	%		●	
Rut depth progression		●	●	
Soil cement resilient modulus	GPa		●	
Standard deviation of rut depth	mm		●	
Thickness of base layer	mm		●	
Thickness of surface layer	mm		●	
Roughness progression		●		
Sand patch texture depth	mm	●		
Shoulder width	m	●		
Structural number		●		
Subgrade CBR	%	●		
Super-elevation	%	●		
Surface type		●		
Surface age	yr	●		
Unit cost for construction and maintenance		●		
Area of previous all crack	%	●		
Area of previous wide crack	%		●	
Construction faults			●	
Crack initiation factor		●	●	
Crack progression factor		●	●	
Cracking retardation time	yr		●	
Maximum acceleration time	m/s^2		●	
Number of base layers			●	
Pothole progression		●	●	

1.6 Research Scope

This research will perform calibration for pavement performance models, RDWE, for environment – age – roughness, crack initiation, crack progression, and general roughness models. As proposed, calibration of the other road performance models (RDWE models) like Raveling and Rutting are not covered in this research due to lack of time series recorded data. (Appendix A Research Proposal)

1.7 Research Outline

This research is composed of seven sections.

The first section addresses the introductory part. It conveys the need for calibration and how series the issue is. Other topics of objective and question of the research are elaborated.

The next section consults and examines different literature regarding calibration of HDM-4 pavement deterioration models. The location the calibration is performed for, methodology implemented, and the result discussion are reviewed.

The third section, addresses matters regarding calibration site information. In this section, road sections based on pavement structure compositions and detail relevant information about the site is presented.

The following section, chapter four, states the conceptual framework of calibration procedure used. Even if each parameter has its own particular calibration steps, the common general approach for all parameters is dealt.

In the fifth chapter the Road Deterioration, Environment and Road Work Effect (RDWE) models calibration for bituminous paved roads is executed and results are discussed. This section explain and reason out the results in line with the magnitude of calibration factors obtained.

The sixth chapter gives the conclusion and recommendation.

Finally, the last chapter highlights hotspots for future works.

2. Literature Review

The HDM-4 predictive relationships have been applied in many developed and developing countries having markedly different technology, climatic and economic environments. The field experiments covered wide ranges of conditions. Though, some local factors are not introduced into the model because they would have made the model's input too complex or their effects could not be determined within the ranges observed (Bennett and Paterson, 2000). For these reasons, calibration of the HDM-4 model to local conditions is necessary and recommended. Moreover, if calibration is not carried out the actual pavement deterioration trend and the HDM-4 predicted deterioration may show large differences. Thus, inadequate local calibration can under or overestimates the budget allocation of highway expenditure (Chai et.al, 2004).

The ‘Guide for Calibration and Adoption’ Vol.5 addresses the issue for calibration as follows.

The objective of HDM-4 analysis is to model roads. This entails predicting the deterioration of the pavement under time and traffic, the road user effects, and the effects of maintenance on the pavement condition and rate of deterioration. As with any model, HDM-4 is a representation of reality. How well the model predictions reflect reality is dependent upon a combination of the:

- Validity of the underlying HDM-4 relationships
- Accuracy and adequacy of the input data
- Calibration factors used in the analysis

Since the underlying HDM-4 relationships have proven to be robust and applicable in a number of countries, the reliability of most HDM-4 analyses depends on the input data and the calibration factors.

2.1 The Need for Calibration

Since the model simulates future changes to the road system from current conditions, the reliability of the results is dependent upon two primary considerations:

- How well the data provided to the model represent the reality of current conditions and influencing factors, in the terms understood by the model; and,

- How well the predictions of the model fit the real behavior and the interactions between various factors for the variety of conditions to which it is applied.

For the above reasons, application of the model involves two important steps:

- **Data input** - A correct interpretation of the data input requirements, and achieving a quality of input data that is appropriate to the desired reliability of the results.
- **Calibration of outputs** - Adjusting the model parameters to enhance how well the forecast and outputs represent the changes and influences over time and under various interventions.

Calibration of the HDM-4 model focuses on the two primary components that determine the physical quantities, costs and benefits predicted for the analysis, namely:

- **Road User Effects (RUE)** - comprised of vehicle operating costs (VOC), travel time, safety and emissions, and
- **Road Deterioration and Works Effects (RDWE)** - comprised of the deterioration of the pavement and the impact of maintenance activities on pavement condition and the future rate of pavement deterioration.

2.2 Model Development Considerations

Early versions of HDM-4 (HCM and HDM-III) relied on simple empirical regression models that were built on field data collected at specific study sites. However, these simple models lacked transferability because they could not show how the results would change when there was a change in the assumed conditions. In the development of HDM-III and HDM-4, a high degree of transferability across different technological and climatic conditions was built into the model. This was achieved through the use of a structured mechanistic-empirical approach in deriving the underlying predictive relationships. This powerful approach combined various insights provided by the theories of motion and vehicle technology, and of pavement material and structural behavior under traffic loading, with a rigorous and advanced statistical analysis of real data gathered from a wide range of vehicle types and road conditions. The validity of the vehicle speed and operating costs models was built up from the four major field studies conducted in Kenya, the Caribbean, Brazil and India (Chesher and Harrison, 1987; and Watanatada et al., 1987a). The validity of the various road deterioration models was demonstrated on independent field data from up to eight different countries and states in climates ranging from hot arid to cold wet (Paterson, 1987).

2.3 Data versus Calibration

An analogy of the sea is useful to illustrate the roles of data and calibration. Data determine the order and magnitude of costs and effects, so these must be of the same order as baseline information, much like the depth of the sea and other attributes like density. Calibration ensures that the height of the waves will be correct under the influence of winds, currents and depths of water.

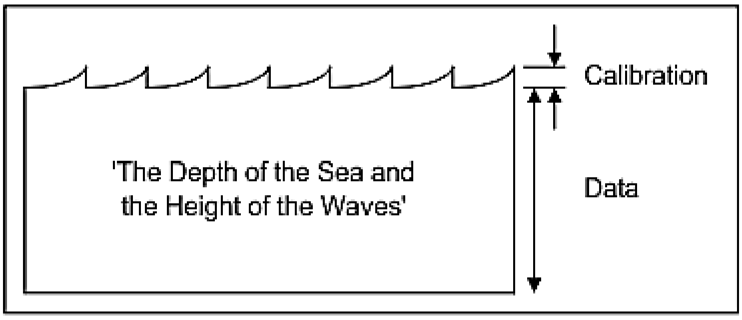

Figure 2.1: Comparison of Data and Calibration (Source: Bennett & Paterson, 2000)

2.4 Input Data

Input data are the basic data items required to run HDM. These consist of parameters that describe the physical characteristics of the pavements and the network, road user data, traffic data, unit costs and economic data.

In establishing input data, the accuracy required is dictated by the objectives of the analysis. If one is doing a very approximate analysis there is no need to quantify the input data to a very high degree of accuracy. Conversely, if one is doing a detailed analysis it is important to quantify the data as accurately as is practical given the available resources.

2.5 Calibration

Calibration is aimed at adjusting the model predictions. The degree of local calibration appropriate for HDM-4 is a choice that depends very much on the type of application and on the resources available to the user.

There are three levels of calibration for HDM-4, which involve low, moderate and major levels of effort and resources, as follows:

Level 1 – Basic application

Level 2 – Calibration

Level 3 – Adaptation

In terms of effort, these three levels can be viewed as weeks, months and years. An analyst should be able to undertake a Level 1 calibration in about one-week. For a Level 2 calibration there is an increase in the amount of effort required so it will take at least a month. Level 3 calibrations require a long-term commitment to basic data collection so their extent spans for a year or more. It must be appreciated that there is a direct relationship between the time and effort expended in setting up HDM-4 and the reliability and accuracy of its output.

a. Level 1 – Basic Application

In order to run HDM-4 it is always necessary to undertake at least a Level 1 calibration; this can be viewed as a set-up investment for the model. Once this has been done, it generally does not need to be repeated for most of the input data files during future applications in the same country since many data items and most model parameters are relatively stable over time (see table 1.1).

A Level 1 calibration is largely based on secondary sources; that is, it is a desk study. For example, the RUE parameters can be estimated using data from sources such as government and industry publications, operator organizations or various RUE reports from previous studies. For road deterioration, the sources would include climate statistics, road traffic and condition statistics, geometric standards, maintenance programs and budgets.

It can be assumed that the bulk of the default HDM-4 model parameters are appropriate for local conditions so only the most critical ones need to be addressed.

While HDM-4 often calls for a wide range of input data and calibration parameters, but only the most important need to be established for use with a Level 1 calibration, so the HDM-4 default values should be used almost exclusively.

b. Level 2 - Calibration

A Level 2 calibration uses direct measurements of local conditions to verify and adjust the predictive capability of the model. It requires a higher degree of data collection and precision than in a Level 1 calibration, and extends the scope. For RDWE, it concentrates on the initiations of surface distress modes, rutting progression, and maintenance effects, and enhances the estimate of environmental impacts.

With Level 2 calibrations, more detailed input data are also collected than with Level 1.

c. Level 3 - Adaptation

A Level 3 calibration is generally comprised of two components:

- Improved data collection and
- Fundamental research

Some data items can be estimated with reasonable accuracy using short-term counts, like the hourly distribution of traffic volume, but the reliability is greatly enhanced by collecting data over more sites over a longer period.

Fundamental research considers the relationships used in HDM-4. This consists of structured field surveys and experimental studies conducted under local conditions which lead to alternative relationships. For example, alternative functions may be developed for predicting new pavement deterioration and maintenance effects functions for different pavement types. Such work requires a major commitment to good quality, well – structured field research and statistical analysis over a period of several years. Pavement deterioration research is a particularly long-term endeavor, typically requiring a minimum of 5 years. (Bennett & Paterson, 2000)

2.6 HDM-4 Calibration Practice in Other Countries

The AUSTROADS National Strategic Research Plan has set up accelerated loading facility under controlled maintenance and environmental condition. These were eight long term pavement maintenance monitored sites, and five sealed granular pavements from 21 long term pavement performance monitored sites to record pavement performance data. Using the data from these sites, they deduce the relative effect of maintenance on performance, estimate of actual rates of deterioration experienced the long term pavement performance sites under varying condition of maintenance, environmental conditions, and loading conditions (Martine et.al, 2004). These sites provide sufficient data for calibrating HDM-4 for different parts of the country, Australia.

Chai and Gray have also calibrated the model for North South Expressway of Malaysia. They set up long term pavement performance (LTPP) recording sites to record pavement performance data. This data was compared with HDM-4’s outputs and they made necessary adjustments to the calibration factors to make its predictions reasonable. Also they used regression analysis and iteration methods for calibration purposes. The general procedure adopted for HDM-4’s roughness progression predictive model parameters calibration is as follows:

1. First, estimation of the initial roughness for each Long term Pavement Performance (LTPP) calibration site after plotting the best-fit progression curve based upon the measured roughness values.
2. Using the initial roughness values, determination of the predicted roughness progression using HDM-4 default value of 1 and plotting the curves for each Long term Pavement Performance (LTPP) site on the same graphs as the measured roughness.
3. Modification of the calibration factor through an iterative process for each LTPP site until the predicted roughness progression curves come as close as possible to the measured roughness progression curves.
4. Adoption of the above derived calibration factors as the Level 2 calibration factors for roughness-age- environment component of the roughness progression model.

It is described that deterioration forecasting is an essential element of an efficient pavement management system. In addition, the HDM-4 model is widely distributed to more than 100 countries around the world. However, many users often point out problems related to calibration limitations, and question the reliability of their results due to the extremely large number of variables, and difficulty in the calibration procedure of deterioration models in the HDM-4. Daeseok Han et.al (2013) tried to address this criticism by introducing Section-based Multi-functional Calibration Method for Pavement Deterioration Forecasting Models. And the author call attention to that current calibration method based on the Network-based approach, which was introduced by the HDM-4 developer, has several limitations in describing the precise deterioration progress, and practical application. In fact, many HDM-4 users often give up implementation due to these reasons. To mitigate these problems, the author suggests an improved calibration method for the HDM-4 deterioration models relevant to the deterioration speed and shape of the curve. The benefit of these new approaches is assumed to be extended to calibrating the software with minimum data, addressing problems on incomplete pavement inventory data which is the most serious problems in the calibration process. The validity of the suggested methods was empirically shown through experience with the national highways in Korea.

The Gauteng Province of South Africa has established 36 Long term Pavement Performance (LTPP) sections which are monitored annually to improve and calibrate PMS performance models. Gustav T. et.al described how the Long term Pavement Performance (LTPP) sections were set out, monitored, and how the collected data influenced the pavement performance models captured in the PMS. Pavement sections were selected to represent pavement conditions found in the province. The selection criteria consisted of:

Three	Traffic Levels (Low, Moderate, High)
Two	Base Types (Granular, Stabilized)
Two	Environments (Dry, Moderate)
Two	Conditions (Poor, Moderate, Good)

Thirty six total sections (3 x 2 x 2 x 3)

For each cell in the matrix a 500 meter long pavement section was selected. This section was divided into 20 subsections (10 in each direction) on which detailed distress data were collected.

2.7 Assessing the Reliability of HDM-4 Predictions

There are a number of techniques that can be used to assess the reliability of HDM-4 predictions. The most appropriate one depends upon the available data and what the objective is.

a. Pavement Performance: Simulation of The Past

One of the easiest methods for assessing the overall reliability of RDWE predictions is to simulate the past condition of the road. This is done in a Level 1 or Level 2 calibration and is always a good check on the model.

In terms of roughness progression, one method for testing the model predictions has been through the use of a "slice-in-time" analysis. This technique uses network roughness data to investigate the roughness-time and/or roughness-pavement strength relationship. Given the variations present in network roughness data it is unlikely that this method will yield useful results. Ndli (1992) applied this technique without success to Thailand. Several factors contributed to the failure of the analysis:

- The ages of pavements were difficult to accurately estimate which meant that the traffic loadings were inaccurate,
- It was difficult to estimate the post-construction roughness,
- The pavement strength was estimated from construction records. However, the variations in roughness along a section of road indicated that there were local variations in strength which were not reflected in the construction records, and
- Variations in traffic growth over the life of the road were not accurately captured.

Thus, any calibration job should take these factors in to consideration prior to the calibration process.

b. Pavement Performance: Controlled Studies

The only way of completely calibrating the HDM-III pavement deterioration model is by conducting a study into the rate of pavement deterioration. Those considering such an undertaking should consult the material in Hodges et al. (1975), Geipot (1982) and Paterson (1987).

It is important that the experiment be designed to gather data on the following items:

- The effect of traffic on pavement deterioration
- The effect of environment on pavement deterioration
- Deterioration rates by pavement type
- Pavement strength effects
- Surface distresses

The sites selected for the study should cover the full range of pavement types and strengths within the country. For each pavement type, pavements covering the complete range of strengths should be included. If there are major differences in the climate over the country, the experiment should be designed to account for this.

The data to be collected will depend upon the objectives of the study. For an adequate calibration the following items need to be collected as a minimum:

- Roughness
- Benkelman beam deflection
- Cracking
- Rut depth

In selecting the sections it should be appreciated that if the pavements have been properly designed for the traffic level it should be difficult to observe traffic loading effects as these have been catered for in the design. One should therefore try and use pavements under-designed for their traffic levels. This consideration is not mandatory but it helps in setting and monitoring Long Term Pavement Performance (LTPP) recording sites to generate pavement deterioration data in short time.

It is important that the test sections be continually monitored and that all the data items are collected at the same time. In a number of studies this was not done and it created problems with the subsequent analysis.

The HDM-4 calibration recommends that a vehicle mounted roughness meter not to be used in measuring roughness. This is because the measurement errors with such instruments are of the same or greater magnitude to the incremental changes in roughness over time. These meters are also prone to calibration problems that may lead to additional errors. The roughness should thus be measured using one of the direct profiling techniques used for roughness meter calibration (for example, Dipstick, Walking Profilometer). This will ensure that the data are of the greatest possible accuracy.

2.8 Sensitivity of HDM-4

It is important to consider general level sensitivity of the model to each parameter so that appropriate emphasis can be given to important parameters and less emphasis to second or third order effects. The influences of individual parameters differ according to the particular parameter, the particular result being considered, and the values assigned to other parameters in the particular analysis. The sensitivity of results to variations in a parameter therefore varies under different circumstances.

There are different approaches which can be used for undertaking sensitivity analyses. The approach used here is the traditional **ceteris paribus** method: changing a single factor while holding all others constant. Mrawira et al. (1998)

Sensitivity analyses were conducted with the HDM-4 RUE and RDWE sub-models so as to determine the levels of sensitivity and to rank them. Sensitivity was quantified by the **impact elasticity**, which is simply *the ratio of the percentage change in a specific result to the percentage change of the input parameter*, holding all other parameters constant at a mean value. The alternative approach, using factoral experiments which combine all the levels of one factor with all levels of all other factors, were not used due to the large number of combinations to consider. Thus, the analysis here does not consider factor interactions.

On the basis of the analyses, four classes of model sensitivity have been established as a function of the impact elasticity. The higher the elasticity, the more sensitive the model prediction is. These classes are listed in Table 2.1. Throughout the remainder of this paper the terms S-I to S-IV will be used to refer to the various sensitivity classes.

Practitioners, as a guide to where their efforts should be directed, should use the results of these sensitivity analyses. Those data items or model coefficients with moderate to high impacts (S-I and S-II) should receive the most attention. The low to negligible impact (S-III and S-IV) items should receive attention only if time or resources permit.

Table 2.1: HDM-4 Sensitivity Classes (Source: Bennett & Paterson, 2000)

Impact	Sensitivity class	Impact elasticity
High	S-I	>0.50
Moderate	S-II	0.20-0.50
Low	S-III	0.05-0.20
Negligible	S-IV	<0.05

One usually assumes the default HDM-4 values for S-III and S-IV items since these will generally give adequate results.

3. Calibration Site Information

3.1 Project Description

The Addis Ababa – Modjo – Hawassa and Addis Ababa – Modjo – Awash roads are part of the interstate highway network, connecting the capital, Addis Ababa, Moyale at the southern border, with Nairobi, the capital of Kenya and Awash at the southern west to Djibouti respectively. The road leads from the capital initially in a south – eastern direction to Modjo. The length of the project section from Addis Ababa to Modjo is 58km. From Modjo, the road heads south, through the Great Rift Valley, running along a number of lakes (Ziway, Abayata, Langano, Shala, and Hawassa) and ends just beyond Hawassa in one direction. These lakes are known for their scenic splendors and abundant bird’s wildlife. There are a number of tourist resorts and a national park in the area. Hawassa is the capital of the southern Nations and Nationalities Region. The length of the project section from Modjo to Hawassa is 205km. The overall length of the project is 263km. On the other hand from Modjo the road heads to Djibouti, which is the main import/export harbor that our country, Ethiopia is using.

From Addis Ababa, the road passes through a number of towns including Kaliti, Akaki, Dukem, Debre Zeit, Meki, Ziway Bulbula, Arsi Negelle, Kuyira and Shashemene. However, the road bypasses the towns of Modjo, Shashemene and Hawassa.

The terrain between Addis Ababa and Modjo is flat to rolling. This section is part of the important road link between the ports of Assab and Djibouti on the Red Sea and the capital. It is the heaviest trafficked road in Ethiopia. The elevation of the road varies between 2,400m above sea level at Addis Ababa and 1,600m at Koka. The average annual rainfall is 1,200mm in Addis Ababa and 800mm in Modjo. (DHV, 2005)

The terrain between Modjo and Hawassa is also flat to rolling. This section is part of the important link with the south of Ethiopia and further to Kenya. The elevation varies from 1,600m above sea level at Koka to 2,000m above sea level at Kuyira town. The average annual rainfall in the section amounts around 800mm. The driest area is between 125km and 220km; the wettest area to be Shashemene and Hawassa. (DHV, 2005)

The Addis Ababa – Modjo road section has been completely rehabilitated as of December 2001. The existing pavement has been milled, shaped and compacted as a sub – base. Then a 20cm crushed aggregate base course was laid on which 10cm of asphalt concrete was constructed in two separate layers. The road width is 7.30m carriageway with 2.35m shoulder width on each side. The shoulders are built up with sub – base material and are sealed with a single surface treatment over the full width. On steep gradients, climbing lanes are constructed to accommodate traffic driving at low speed. The approach to the Addis Ababa ring road interchange is upgraded to four lanes. The traffic sings and road marking were put in place.

The design further provided for the construction of parking lanes and paved ditches in urban areas. Unpaved ditches have been constructed in rural areas where required. Existing bridges were repaired. In the town of Shashemene a bypass was constructed, approximately 5km in length, including two new culverts. The Shashemene through road is rehabilitated to sub – base level.

The design modification and construction details as per DHV Consultants “Final Contract Report”, November 2005, are summarized and presented as follows.

3.2 Pavement Structure Background

Preceded to the final design for the Addis Ababa – Modjo – Hawassa road, a preparation design study has been performed. Initially the rehabilitation for the Addis Ababa – Modjo section were only meant to be cosmetic and should be limited as much as possible as a major rehabilitation after some years and a possible extension to a dual carriageway was anticipated. The geometry of the Addis Ababa – Modjo section as well the Modjo – Hawassa section was not to be modified, maybe only some lifting of the vertical alignment on some sections of the Modjo –Hawassa road was required. As the study progressed, an Interim Report was issued on 05 April 1995. It was concluded that, based on visual inspections, only resealing of the Addis Ababa – Modjo road would not be sufficient. In addition, it was noted that the existing shoulders were in a bad condition at many locations, which meant that they were too narrow, too steep or worn out. The same report also noted that both the horizontal and the vertical alignments were not to the standards at some locations. Further, the rapid increase of traffic was noted, new traffic counts were strongly advised. The consultant conducted extensive investigations and calculations for the rehabilitation of the existing pavement. This also included a detailed investigation of culverts and bridges as to their drainage properties and structural conditions completed the investigation.

It became clear that a simple resealing of the Addis – Modjo road would not suffice to guarantee a long enough lifetime of this important road. Preliminary outcomes concluded the need of an in-depth investigation and extensive design to a far higher extent in terms of complexity, which was accommodated in the first rider.

The above resulted in a design with overlay for the rehabilitation of the Addis Ababa – Modjo road section.

As per the report, a new pavement condition survey performed at the start of the construction phase revealed that the sections, as indicated in the pavement condition survey report of May 1995, were that much deteriorated that repair and overlay would become a very costly operation. Therefore a change of strategy for the rehabilitation of the Addis Ababa – Modjo road section was taken on by the Ethiopian Roads Authority. In some cases modifications of design and changes of specifications were required to improve the initial above described design for the Addis – Modjo – Hawassa road. (DHV Consultant, 2005)

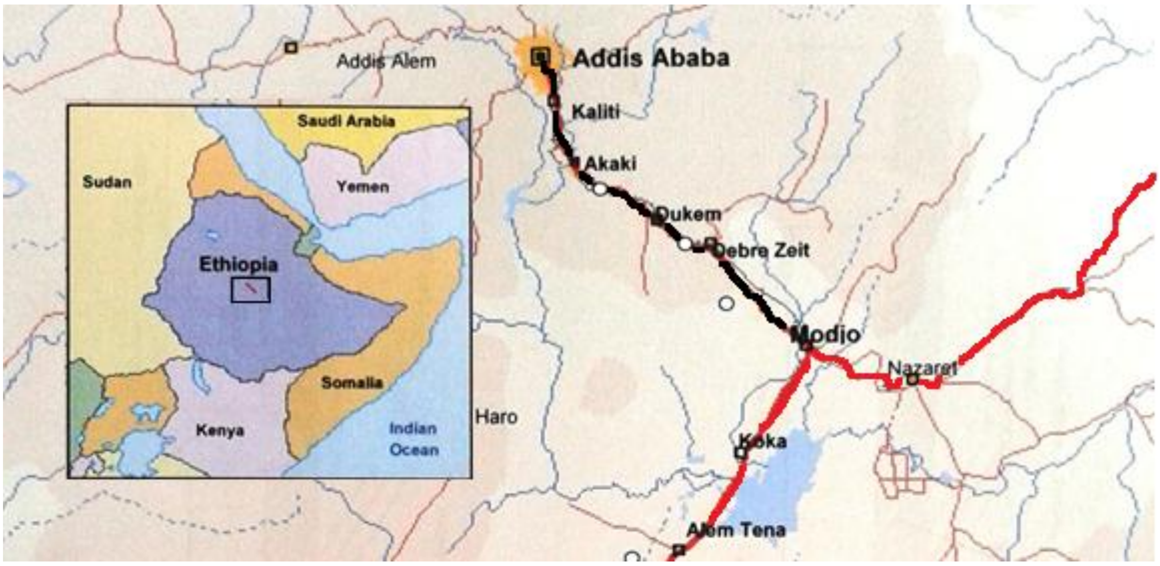

Figure 3.1: Location Map (Source: DHV Consultant, 2005)

a. Change Of Strategy for Rehabilitation of Addis Ababa – Modjo

The final construction report mentioned that, on Friday 19th June 1998 the Supervisor presented a revised typical cross section for the new strategy on the Addis Ababa – Modjo road.

The new strategy covered:

- Reconstruction of the 59.5km of Addis Ababa – Modjo road by milling an average 200mm of the existing carriageway, using it as a sub – base and topping it with 200mm of crushed aggregate base course and 100mm of asphalt concrete in two layers;
- 36.5km of normal section 7.30m wide in the rural sections (as per typical cross section drawings);
- 13.1km of town road sections 12.3m wide;
- 10.4km of road with 3.5 wide climbing lanes to accommodate traffic driving at low speed constructed at the following locations:
  - Km. 17+500 to 19+400 left hand side;
  - Km. 20+100/200 to 22+100/200 right hand side;
  - Km. 30+300/400 to 27+700/800 right hand side;
  - Km. 30+460/560 to 34+530/630 left hand side.
- Amendment to the edge of pavement / curb detail at paved ditch locations within town sections on the Addis Ababa – Modjo road section.

b. Full width sealing of shoulders Addis Ababa – Modjo section

To avoid possible future maintenance problems it has been implemented the single surface treatment over the full width of the shoulder rather than only 1.50m as designed on the Addis Ababa – Modjo section to avoid possible maintenance problems later.

For Addis Ababa – Modjo section, where the shoulder is 2.35m the width of the surface treatment is therefore changed from 1.50m to 2.35m.

3.3 Rainfall

Rainfall data is used in the calibration process to determine the moisture class of the calibration site. These classes have at least 300mm annual rainfall differences. Thus reference is made from the same report, DHV consultant 'Final Contract Report', for a nine years average monthly rainfall data. This data has been employed for the design of major rehabilitation.

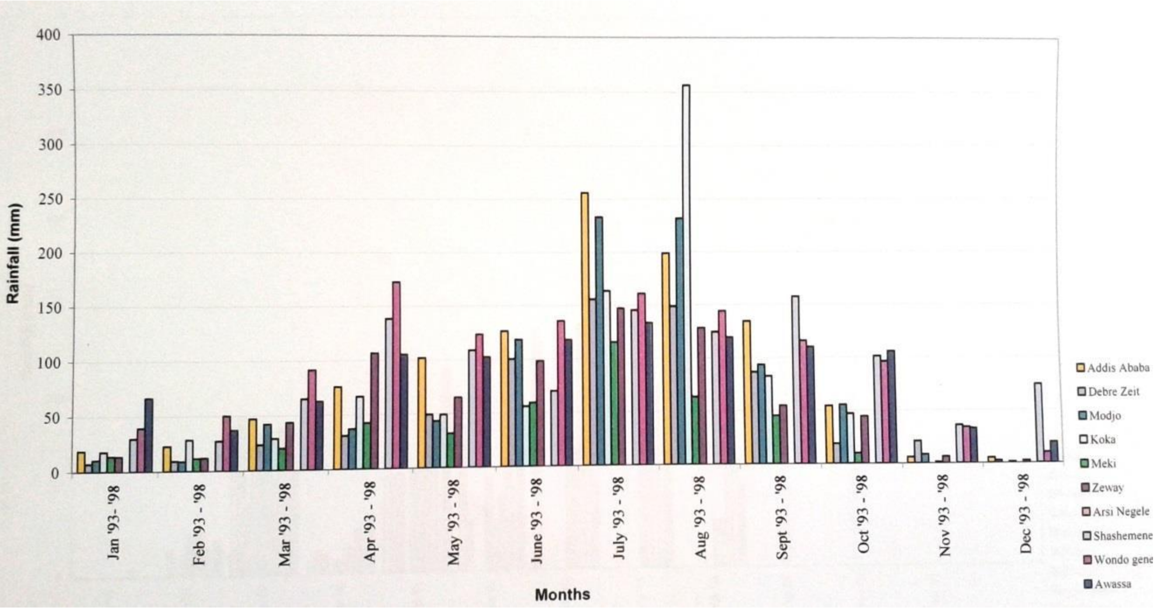

Figure 3.2: Six Years Average Monthly Rainfall (Source: DHV consultant, 2002)

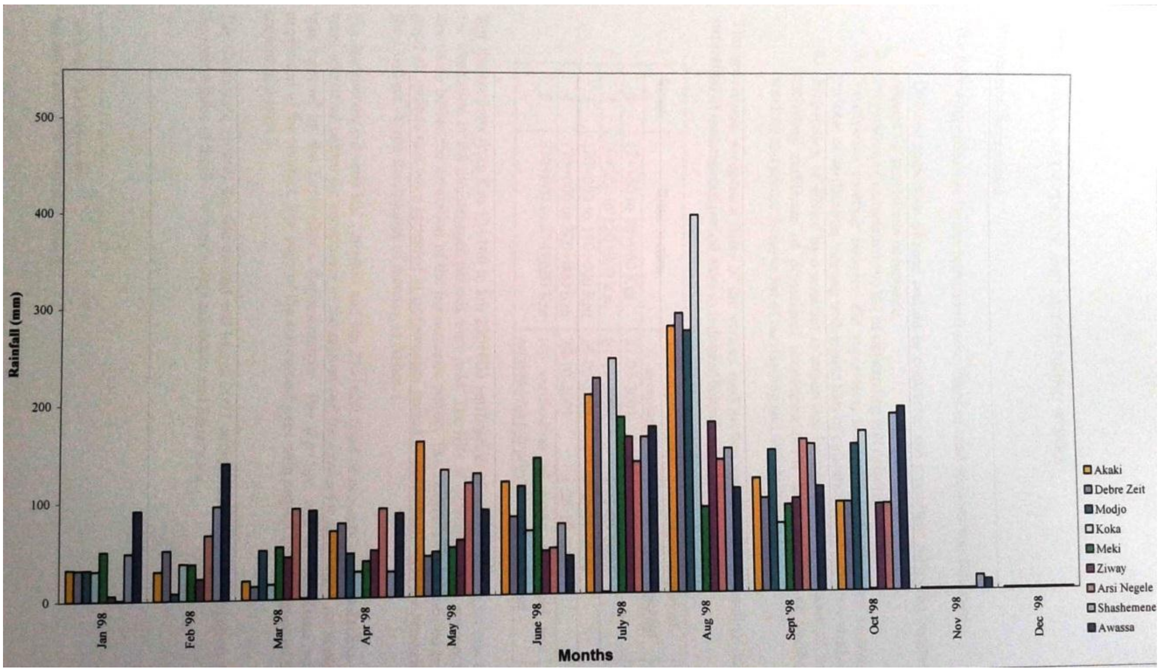

Figure 3.3: Monthly Rainfall Data for 1998 (Source: DHV consultant, 2002)

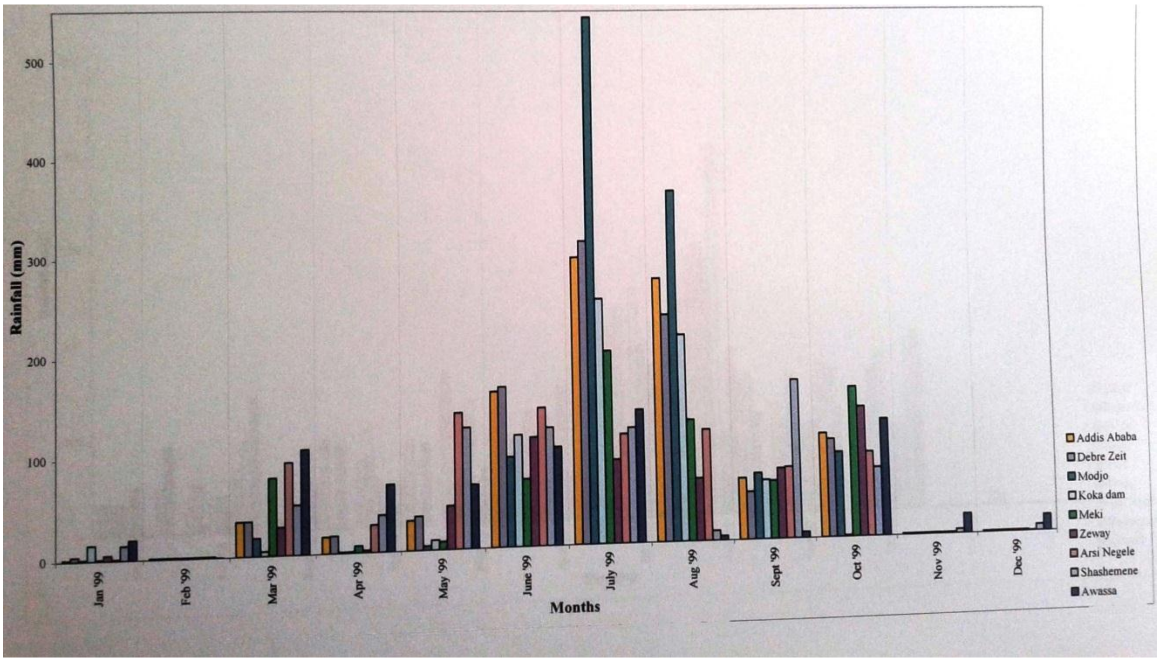

Figure 3.4: Monthly Rainfall Data for 1999 (Source: DHV consultant, 2002)

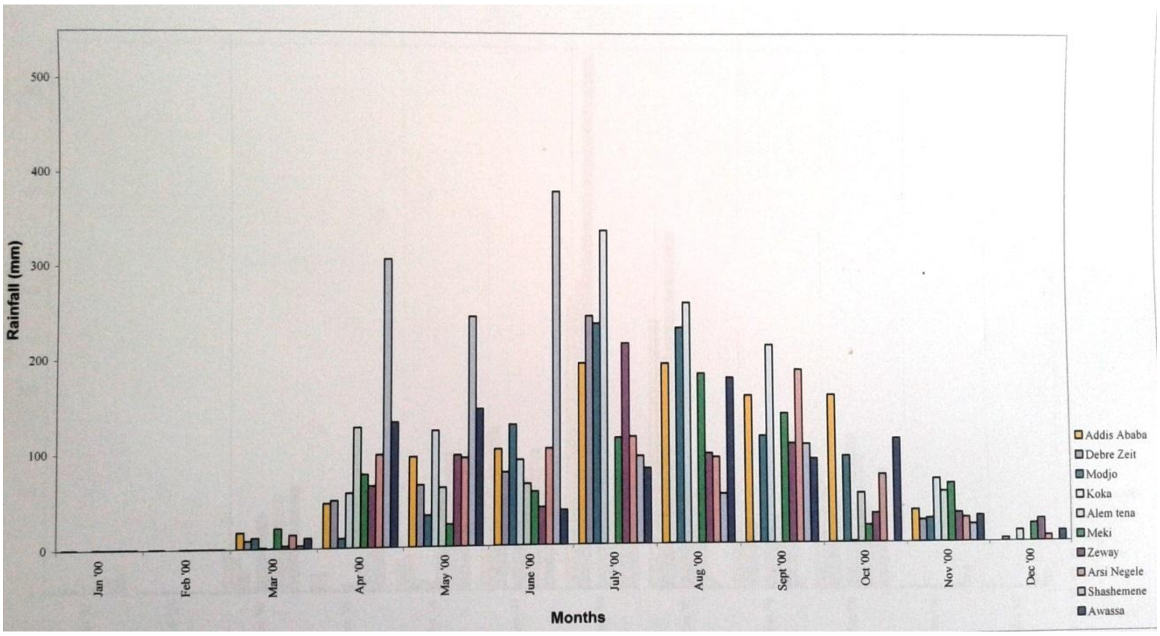

Figure 3.5: Monthly Rainfall Data for 2000 (Source: DHV consultant, 2002)

4. Methodology

4.1 General Approach

Each Road Deterioration, Environment and Road Work Effects (RDWE) model calibration implement distinct approaches which are clearly discussed in the calibration section. However, assessing the adequacy of HDM-4's predictions generally is done by comparing the model predictions to known data, as the calibration and adoption guide dictates. Thus, data on the current pavement conditions of a number of pavements of known ages and HDM-4 predictions of pavements condition of the same age and same attributes are assessed whether HDM-4 was giving appropriate predictions.

There are two considerations when comparing predicted and observed data: Bias and Precision.

Bias is systematic difference that arises between the observed and predicted values. For instance, if the predictions are always 10 per cent lower than the observed data. The formal definition of bias is the difference between the mean predicted and mean observed values.

Precision measures how closely the observed and predicted data are to each other. It is represented by the reciprocal of the variances; that is, it is reflected by the scatter when plotting the observed versus predicted data. Precision is influenced the inherent stochastic variations of most natural processes, measurement and observational errors, and unexplained factors omitted from relationships in the model.

Figure 3.1 illustrates both of these concepts for four scenarios:

- Low Bias - High Precision (see Figure 4.1A)
- Low Bias - Low Precision (see Figure 4.1B)
- High Bias - High Precision (see Figure 4.1C)
- High Bias - Low Precision (see Figure 4.1D)

In Figure 4.1 the shaded ellipse represents observed data which has been plotted against predicted data. The solid line at 45° is the line of equality, where the observed and predicted are equal.

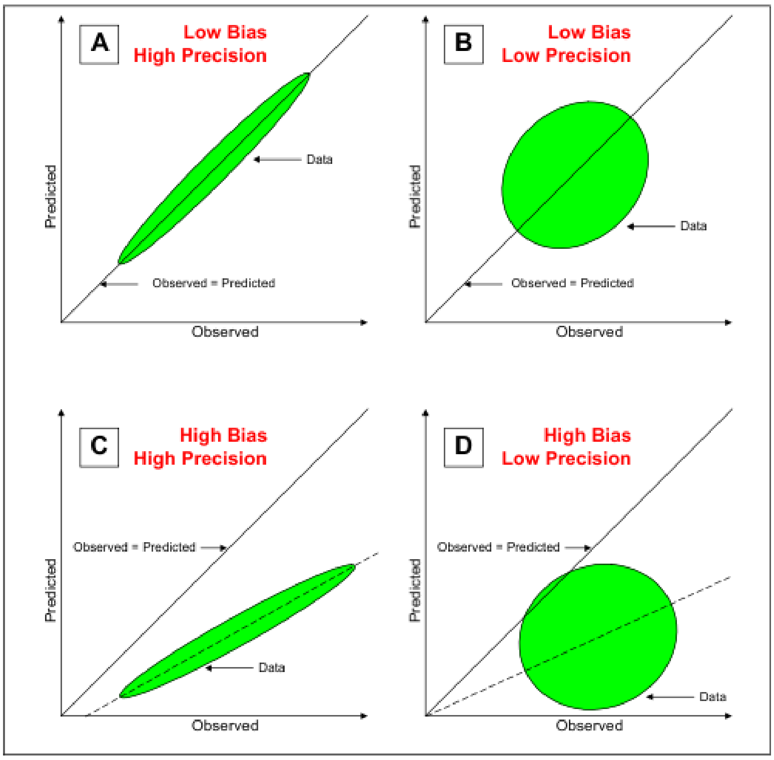

Figure 4.1: Examples of Bias and Precision (Source: Bennett & Paterson, 2000)

4.2 Correction Factors

Bias arises because of systematic differences in the observed versus predicted values. Correction factors are used to correct for the bias. As shown in Figure 4.2, there are two types of calibration factors: **rotation** and **translation**. Either or both of these may be present.

In the simplest case, the bias is established as the ratio of the mean observed to mean predicted (Bennett & Paterson, 2000). Thus, the correction factor is:

CF_{rot} = Observed Mean / Predicted Mean (1)

Where: CF_{rot} is the correction factor for bias

This is referred to as the rotation correction factor because, as illustrated in Figure 4.2-A, the predictions are rotated down to where they correspond to the observed data. The translation factor is used when there is a constant difference between the observed and predicted values across all conditions (see Figure 4.2-B). An example of this is where the vehicle operating costs are overestimated due to overheads being improperly included. In this instance the correction factor is:

CF_{trans} = Predicted Mean - Observed Mean … (2)

Where: CF_{trans} is correction factor for precision

Figure 4.2-C also shows the third, and common, scenario where there is a combination of rotation and translation.

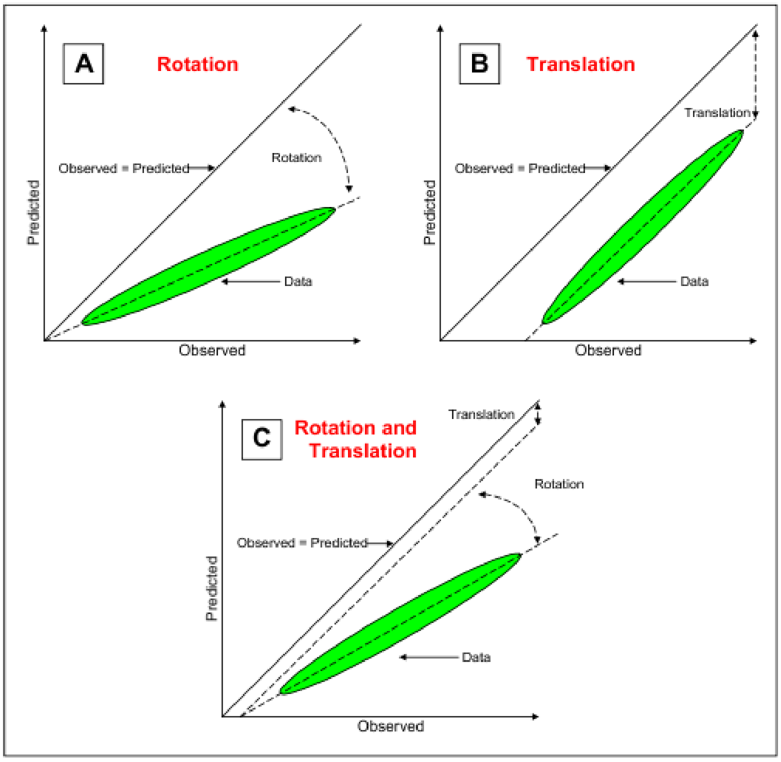

Figure 4.2: Correction Factors (Source: Bennett & Paterson, 2000)

The goal of calibration is defined here with respect to the impact of an individual parameter, but very approximate in respect of the impact of all parameters. This is because each of many data items and model parameters may have their own biases, and the processes being modeled by HDM-4 are complex. This is extremely difficult to determine the net bias effects of multiple parameters.

The goals of calibration, excluding the fundamental lack of fit of the model, are to reduce any bias of the predictions by the model to acceptable levels. Level 2, being of a higher standard, is intended to produce less residual bias in the model’s predictions than a Level 1 calibration.

5. Analysis and Result Discussion

5.1 Calibration of Road Deterioration, Environmental and Road Work Effects (RDWE) Models for Bituminous Paved Roads

The HDM-4 Guide for Calibration and Adoption discuses that flexible pavement deterioration and works effects (RDWE) model has seven deterioration adjustment factors.

The sensitivity of each factor is quantified by the Impact Elasticity, which is the ratio of the percentage change in a specific result to the percentage change of the input parameter, holding all other parameters constant at a mean value. On the basis of this analysis, four classes of model sensitivity have been established as a function of the impact elasticity. The higher the elasticity, the more sensitive the model prediction is. These classes are listed in Table 5.1. Throughout the remainder of this paper the terms S-I to S-IV will be used to refer to the various sensitivity classes.

Table 5.1: HDM-4 Sensitivity Classes (Source: Bennett & Paterson, 2000)

Impact	**Sensitivity class**	**Impact elasticity**
High	S-I	>0.50
Moderate	S-II	0.20-0.50
Low	S-III	0.05-0.20
Negligible	S-IV	<0.05

Table 5.2 shows the impact elasticity class for the seven factors combined with the typical range of values of the factors to give a potential net impact. Six criteria representing different applications were used in the analysis and these are listed in the footnote to Table 5.2.

Table 5.2: Ranking of Impacts of Road Deterioration Factors (Source: Bennett & Paterson, 2000)

Deterioration factor	**Impact class for given criteria[1]**						**Impact Elasticity**	**Typical value of factor**	**Net Impact (%)**	**Sensitivity class**
	1	2	3	4	5	6				
Roughness-age environment	D	D	B	C	B	B	0.2	0.2 - 5.0	10	High
Cracking initiation	A	C	B	B	C	B	0.25	0.5 - 2.0	6	
Cracking progression	A	C	C	C	C	C	0.22	0.5 - 2.0	6	
Rut depth progression	D	A	B	D	C	C	0.1	0.5 - 2.0	3	Low
Roughness progression general	D	D	B	D	C	B	0.09	0.8 - 1.2	1	
Potholing progression	D	D	C	B	C	D	0.03	0.3 - 3.0	2	
Raveling initiation	D	D	D	C	D	D	0.01	0.2 - 3.0	1	

1: each number in the impact class representation is as follows:
Cracking, (1)
Rut depth, (2)
Roughness, (3)
EIRR for patching, (4)
EIRR for reseal, (5)
EIRR for overlay, (6)
Where: EIRR mean Economic Internal Rate of Return

Impact sensitivity:
A = S-I
B = S-II
C = S-III
D = S-IV

Table 5.2 is read as, for instance, the roughness – age - environment factor has D letter in the first column (1) of impact class. This means pavement cracking (code 1) is fourth sensitive class (with less than 0.05 impact elasticity) for roughness. The net impact of each factor is presented indicating the overall effect of each factor variation in the HDM-4 software.

Thus, the roughness-environment factor is clearly the most important, due to the wider range of its values, followed by the cracking initiation and progression factors. Thus these factors highly influence the model prediction. The general roughness progression factor has low priority, despite its moderate sensitivity, because its range is small based on many inter-country validation studies.

5.1.1 Level 1 - Basic application

The level one calibration will adjust the first three deterioration factors, roughness – age – environment, crack initiation and progression but general roughness model does not need adjustment for this calibration level. (Bennett & Paterson, 2000)

i. Roughness – Age – Environment Adjustment Factor: (Sensitivity Class One, S-I)

This factor determines the amount of roughness progression occurring annually on a non-structural time-dependence basis. It is related to the pavement environment and is effectively an input data parameter rather than a calibration adjustment. The factor adjusts the environment coefficient, m, which has a base value of 0.023 in the model, representing 2.3% annual change independent of traffic, that is

$$\Delta R_{te} = K_{gm} 0.023 R_t \qquad (3)$$

Where:

ΔR_{te} is the change in roughness component due to environment in 1 – year analysis time increment
K_{gm} is the roughness – age – environment factor
R_t is the roughness at the beginning of year t

For a Level 1 Calibration, the values are established based on the general environmental conditions and the road construction, and drainage standard. This is done as follows:

Step 1 To identify the environment applicable to the immediate vicinity of the road project in terms of the classifications provided in Table 5.3. Since the road is located in tropical zone with temperature range of 20 – 30 C^o this temperature class is adopted. And as per the rainfall data presented in calibration site description section, the average annual rainfall of the three cities, Addis Ababa, D/Zeit and Modjo amounts 873mm (see section 3.3). Thus the moisture classification of the road will be sub – humid.

Table 5.3: Classification of Road Environment (Source: Bennett & Paterson, 2000)

Temperature classification	**Description**	**Typical temperature range (°C)**	
Tropical	Warm temperatures in small range	20 to 35	
Subtropical - hot	High day cool night temperatures, hot-cold seasons	-5 to 45	
Subtropical - cool	Moderate day temperatures, cool winters	-10 to 30	
Temperate - cool	Warm summer, shallow winter freeze	-20 to 25	
Temperate - freeze	Cool summer, deep winter freeze	-40 to 20	
Moisture classification	**Description**	**Typical moisture index**	**Typical annual precipitation (mm)**
Arid	Very low rainfall, high evaporation	-100 to -61	< 300
Semi-arid	Low rainfall	-60 to -21	300 to 800
Sub-humid	Moderate rainfall, or strongly seasonal rainfall	-20 to 19	800 to 1600
Humid	Moderate warm season rainfall	20 to 100	1500 to 3000
Per-humid	High rainfall, or very many wet-surface days	> 100	> 2400

Step 2 According to the environmental classification, the appropriate value of m is selected from Table 5.4. Thus m = 0.020

Table 5.4: Recommended Values of Environmental Coefficient, m (Source: Bennett & Paterson, 2000)

Moisture classification	**Temperature classification**			
	Tropical	**Sub-tropical non-freezing**	**Temperate – shallow freezing**	**Temperate – extended freezing**
Arid	0.005	0.010	0.025	0.040
Semi-arid	0.010	0.016	0.035	0.060
Sub-humid	0.020	0.025	0.060	0.100
Humid	0.025	0.030	0.100	0.200
Per-humid	0.030	0.040		

Step 3 The next step is to determine the effective m-value, m_{eff} by multiplying m by a factor K_m which is determined according to the standard of road construction and drainage. Referring to Table 5.5, for normal standard material quality, adequate drainage and formation for local moisture conditions, and moderately maintained road construction standard $K_m = 1.0$. Thus m_{eff} is calculated as follows:

$$m_{eff} = mK_m = 0.020 * 1.0 = 0.020 \qquad (4)$$

Where: m_{eff} effective environmental coefficient

K_m adjustment for material and drainage

Table 5.5: Modifying Factor of Environmental Coefficient for Road Construction and Drainage Effects (Source: Bennett & Paterson, 2000)

Construction and drainage	**Non-freezing environments**	**Freezing environments**
High standard materials and drainage; for example, motorways, raised formation, free-draining or non-frost-susceptible materials, special drainage facilities.	0.6	0.5
Material quality to normal engineering standards; drainage and formation adequate for local moisture conditions, and moderately maintained.	1.0	1.0
Variable material quality in pavement, including moisture or frost-susceptible materials; drainage inadequate or poorly maintained, or formation height near water table.	1.3	1.5
Swelling soil subgrade without remedial treatment	1.3 - 2.0	1.2 - 1.6

Step 4 Is to calculate $K_{gm}$from m_{eff} as follows:

$$K_{gm} = \frac{m_{eff}}{0.023} = \frac{0.020}{0.023} = 0.8695652173913 \approx \mathbf{0.870} \qquad (5)$$

ii. Cracking Initiation Adjustment Factor: (Sensitivity Class One, S-I)

Cracking initiation is predicted in terms of the time to the first visible crack, and when the surfacing age first exceeds this time, cracking is deemed to begin. The adjustment factor is a simple multiplier of the time to first crack, that is:

$TYcra = Kcia\,TY$ (Predictive relationship for relevant surfacing type) (6)

Where:

$TYcra$ is the time predicted to first visible crack in years
$Kcia$ is the calibration factor
TY is the time to first visible crack in years observed

The observed crack is the interactive fatigue effects of pavement strength, traffic loading, and the durability effects of ageing.

However, what the above relationships could not do is to define how satisfactory were the material design, manufacture and construction quality, or define the oxidizing power of the environment, except in average terms. The calibration adjustment, ($Kcia$), is therefore assumed to compensate for these in specific situations.

Assuming the predicted structural effects are correct, the Level 1 calibration attempts to estimate the calibration factor by estimating the quality of each bituminous surfacing type, etc. The following steps are followed and classification is implemented as per the prevailing fact of the road information.

Step 1 To evaluate the quality of the available refined bitumen:

- High quality (HB)
  Refined by international oil companies for specific uses in the highway industry, from selected crude sources with low wax content
- Low quality (LB)
  Produced by local refineries or from high-wax crude sources, with poor oxidation resistance

Step 2 Evaluate the likely oxidation by the atmosphere on exposed road surfaces given the local climate:

- Highly oxidizing (HO)
  Low cloud cover, high incidence of sunshine, high altitudes, depleted ozone area
- Moderately oxidizing (MO)
  Mixed conditions of sunshine hours and cloud cover, low to medium altitudes
- Low oxidizing (LO)
  Frequent cloud cover, low altitudes, cool sub – humid or high rainfall climate

Step 3 Evaluate the construction quality:

- High (HC)

  Careful binder temperature control, adequate binder content, low air voids in asphalt mixtures (or good compaction), high standard of mixing plant and compaction equipment, use of medium or soft bitumen (for example, 80/100 penetration or higher)
- Fair (FC)

  Moderate or variable adherence to the qualities above
- Low (LC)

  Frequent over-heating of binder, low binder content, high air voids in asphalt mixtures (or poor compaction), extensive use of hard bitumen (40/50 or 60/70 penetration).

In the above steps a high quality bitumen, moderate oxidation and fair construction quality is considered. Then the final step is:

Step 4 To select adjustment factor based on binder quality, oxidizing climate and construction quality from Table 5.6 to be $\boldsymbol{K_{ci} = 1.0}$.

Table 5.6: Level 1 Adjustment Factor for Cracking Initiation (Source: Bennett & Paterson, 2000)

Construction Quality	**Bitumen quality**	**Oxidizing climate**		
		High	Medium	Low
High	High	1.0	1.2	1.5
	Low	0.8	1.0	1.1
Medium	High	0.8	**1.0**	1.1
	Low	0.6	0.8	0.9
Low	High	0.6	0.8	0.9
	Low	0.4	0.6	0.7

iii. Cracking Progression Adjustment Factor: (Sensitivity Class One, S-I)

The Calibration and Adoption Guide reveal that the rate of cracking progression in the analysis year is a function of the area of cracking, surfacing type and other factors. Thus the adjustment factor multiplies the amount of increase in area of cracking.

For a Level 1 calibration, it is recommended that the factor be taken as the inverse of the cracking initiation factor, that is:

$$K_{cp} = \frac{1}{K_{ci}} = \frac{1}{1.0} = 1.0 \qquad (7)$$

iv. Rut Depth Progression Adjustment Factor: (Sensitivity Class One, S-I)

The increase in rut depth prediction is a strong negative function of the existing Rut depth, Degree of Compaction, Pavement strength and whether the surface is overlay or not and positive function of Traffic loading, Cracking and Rainfall.

The calibration factor is a direct multiplier of the predicted increase so a higher factor accelerates rut depth progression. However, the calibration guide dictates that the 1st level calibration is not considered necessary.

v. General Roughness Progression Factor: (Sensitivity Class Three, S-III)

The structure and coefficient values of the roughness progression prediction have proved to be very reliable throughout many countries and climates, so no adjustment is considered necessary in this factor in a Level 1 calibration.

vi. Raveling Initiation Factor: (Sensitivity Class Three, S-III)

Since raveling and potholing are not extensive in practice and as the adjustment factor for raveling initiation has low impact on most applications, it was reasonable to retain the default value of 1 for it.

vii. Potholing Progression Adjustment Factor: (Sensitivity Class Three, S-IV)

With the same reason, as the adjustment factor for potholing progression has low impacts on most maintenance alternatives except patching and extremely low maintenance, it is reasonable in most cases to adopt the default value of 1.

5.1.2 Level 2 - Calibration of Primary Relationships

Prior to the second level calibration process, it is appropriate to visualize the general picture of the calibration site. Due to the fact that the calibration site may consist different pavement structures located in different location having distinct climatic conditions, the whole road stretch is section based on the following criteria.

Based on pavement structural thickness and construction activity:

1. Horizontal and/or vertical alignment change from the existing road section:
    i. 68+610 to 68+740km:
        - With 300mm sub-base; 200mm crushed stone base material and 100mm asphalt concrete in two layers,
    2. 68+750 to 68+850 Km:
        - 300mm selected fill, 300mm sub – base, 200mm crushed aggregate base course and 100mm asphalt concrete;
    3. 68+860 to 69+740 Km:
        - 200mm sub – base, 200mm crushed aggregate base course and 100mm asphalt concrete
2. From 68+750 Km to 68+850 Km a section of black cotton soil was found and had to be removed and replaced by selected fill:
    - 200mm sub-base, 200mm base course thickness, and 100mm asphalt concrete thickness is provided.
3. The remaining section of the road is constructed by milling the existing (asphalt) pavement, and by considering this as a sub – base, no additional sub – base material was required, and limiting the sub-base thickness to 200mm and surface course thickness of 100mm of asphalt concrete lied by two layers.

However, for simplicity and due to the fact that most of the road section is rehabilitated by milling the existing road surface, this section is considered to be the representative section. This decision also gives another advantage of assuming same load support capacity beneath the base course.

Table 5.7: Section Type According to Pavement Structural Thickness (DHV, 2005)

No.	Description	Length (Km)	AC Surfacing (in)	Base course (in)	Sub-base (in)	Capping layer (in)	SN
1	**Sections with horizontal/vertical alignment change**						
i	68+610 to 68+740	0.13	3.94	7.87	11.81	-	4.69
ii	68+750 to 68+850	0.10	3.94	7.87	11.81	11.81	4.69
iii	68+860 to 69+740	0.88	3.94	7.87	7.87	-	4.25
	Total	1.11					
2	**Sections constructed by milling the existing pavement**						
i	All segment rather than mentioned above	58.39	3.94	7.87	7.87	-	4.25

Next, it is necessary to have equivalent sub-grade support for the prevailing traffic. The AASHTO design monograph was used to extrapolate the subgrade bearing capacity in modulus of resilience. Therefore, for the whole segment of the road rather than section of realignment, with structural number of 4.25, the subgrade support value is read to be 27Ksi (186MPa).

Then the Adjusted Structural Number is computed using the formula presented in Analytical Frame work and Model Description Vol. 4 of HDM-4. It is presented as follows:

$$\mathrm{SNP} = \mathrm{SNBASU} + \mathrm{SNSUBA} + \mathrm{SNSUBG} \tag{8}$$

$$\mathrm{SNBASU} = 0.0394 \sum_{i=1}^{n} a_i h_i \tag{9}$$

$$\mathrm{SNSUBA} = 0.0394 \sum_{j=1}^{m} a_j \begin{Bmatrix} \left(\frac{b_0 \exp\left(-b_3 z_j\right)}{-b_3} + \frac{b_1 \exp\left(-(b_2+b_3) z_j\right)}{(b_2+b_3)}\right) - \\ \left(\left(\frac{b_0 \exp\left(-b_3 z_{j-1}\right)}{-b_3} + \frac{b_1 \exp\left(-(b_2+b_3) z_{j-1}\right)}{(b_2+b_3)}\right)\right) \end{Bmatrix} \tag{10}$$

$$\mathrm{SNSUBG} = [\mathrm{b}_o - b_1 \exp(-b_2 \mathrm{zm})][\exp(-b_3 \mathrm{zm})]\,[3.51 \log_{10} CBR - 0.85(\log_{10} CBR)^2 - 1.43] \tag{11}$$

Where:

SNP	adjusted structural number of the pavement
SNBASU	contribution of surfacing and base layers
SNSUBA	contribution of the sub-base or selected fill layers
SNSUBG	contribution of the subgrade
n	number of base and surfacing layers (i=1,2,…,n)
a_i	layer coefficient for base or surfacing layer *i*
h_i	thickness of base or surfacing layer *i* (mm)

m	number of sub-base and selected fill layers (j = 1,2,…,m)
z	depth parameter measured from the top of the sub-base (underside of base) (mm)
z_j	depth to the underside of the j^{th} layer (z_0 = 0) (mm)
CBR	in situ subgrade CBR
a_j	layer coefficient for sub-base or selected fill layer j
b_0, b_1, b_2, b_3	model coefficients referred from

The Modulus of Resilience values for soils must be correlated to the old Soil Support Value, CBR, so as to take full advantage of the Structural Number equation.

An accepted approximate correlation is (ERES Consultant, 1987):

$$MR(Psi) = 1500 * CBR \qquad (12)$$

Where:	MR	is resilient modulus, [Psi]
	CBR	is California Bearing Ratio, [%]

This equation is used to determine a CBR value of 18% for 27Ksi of MR. Other parameter values from the final construction of road report are summarized in Table 5.8.

Table 5.8: Adjusted Structural Number Parameters (DHV, 2005)

n	2
$h_{i=1,2}$	100mm, 200mm
$a_{i=1}$	0.44
$a_{i=2}$	0.14
m	1
z	200mm
$z_{j=1}$	200mm
CBR	18%
$a_{j=1}$	0.11
b_0, b_1, b_2,b_3	1.6, 0.6, 0.008, 0.00207

Thus $SNP = 2.8368 + 0.9119 + 1.5999 \approx \mathbf{5.35}$

The cumulative traffic loading for 12 years, time from service opening (2001 GC) up to the analysis year (2013 GC), is computed and tabulated in Table 5.9.The procedure followed is:

1. To obtain traffic data of the standard vehicle categories from service opening year (2001 GC) up to the analysis year (2012 GC) (ERA traffic survey, 2001-2012 GC)
2. To sum up the 12 years cumulative traffic repetition for each vehicle classes
3. To compute the Equivalent Axel Load Factor (EALF) for each vehicle class as per the number and weight of axels of each vehicle class using the following formula,

$$\text{EALF} = \left(\frac{L_x}{L_s}\right)^{4.5} \qquad (13)$$

Where: L_x is axel load on the vehicle

L_s is standard load of a single axel (18kip for single axels, 32kip for tandem and 48kip for tridem axel)

4. To multiply cumulative traffic of each classes with their own EALF and to sum all products to find the total Equivalent Standard Axels (ESA).

Table 5.9: Traffic Loading as of 2012 GC (partial traffic data given in Appendix C)

	Cars	Land Rovers	Small Buses	Large Buses	Small Trucks	Medium Trucks	Heavy Trucks	Truck Trailers
AADT$_1$	673	969	833	576	719	843	880	1,028
EALF	0.00	0.00	0.01	0.22	0.01	1.16	1.69	11.00
12th year Cumulative traffic (10^6) per lane	1.95	2.81	2.42	1.67	2.09	2.45	2.56	2.99
ESA (10^6) for each Class	0.00	0.00	0.02	0.37	0.02	2.84	4.32	32.85
Total ESA (10^6)								**40.42**

i. Roughness – Age – Environment Adjustment Factor: (Sensitivity Class One, *S*-I)

This factor determines the amount of roughness progression occurring annually on a non-structural time-dependence basis. It is related to the pavement environment and is effectively an input data parameter rather than a calibration adjustment. The factor adjusts the environment coefficient, m, which has a base value of 0.023 in the model, representing 2.3% annual change independent of traffic, that is

$$\Delta R_{te} = m_{eff} R_t = K_{gm} m_0 R_t = K_{gm} 0.023 R_t \quad (14)$$

Where:

ΔR_{te}	is the change in roughness component in 1 – year analysis time increment due to environment for year t
m_{eff}	is the effective environment coefficient (discussed in section 5.1.1)
R_t	is the roughness at the beginning of year t
K_{gm}	is the roughness – age – environment factor

For this calibration the pavement environment coefficient, m, can be estimated directly from samples of pavements selected in several different environmental zones in the calibration section. In case of considerable difference in climate along with the road traversed, an average value each of parameter is considered. However, in this research case the entire calibration segment is located reasonably in the same climatic zone. Therefore, the whole road segment is considered for one environment coefficient.

Field Measurements

According to the Ethiopian Roads Authority (ERA) condition report of the year 2013GC, the Addis Ababa – Modjo road is generally in a Fair condition. Referring this report and different year's traffic counts, the necessary field measurement values are computed and tabulated in Table 5.10.

Table 5.10: Input Parameters for Pavement Environment Coefficient

Parameter	Code/[unit]	Value
Pavement age	AGE3	12
Cumulative traffic loading	NE ESA	40.42
Roughness, RI_0	Initial IRI, [m/km]	1.5
Roughness, RI_t	IRI at t=12th yr, [m/km]	3.1
Pavement structural number	SNP	5.35
Pavement type	-	Asphalt concrete
Drainage environment type	-	Tropical/semi-humid

Evaluation

The environment parameter m is estimated directly from the summary model for roughness progression (Paterson and Attoh - Okine, 1992), assuming the rest of the summary predictive model is correct, as follows:

1. The initial roughness is estimated by considering a standard original roughness for a new asphalt concrete road. Which is $IRI_o = 1.5$
2. Estimation of m from the summary model rewritten as follows and using a spread sheet tool:

$$m = \frac{\{\ln[RI_t] - \ln[RI_o + 263\, NE(1+SNP)^{-5}]\}}{AGE3} \qquad (15)$$

$$m = 0.0169 \approx \mathbf{0.017}$$

The calibration can be applied in two ways:

1. Thus, for pavements with **similar** pavement structure and environmental condition, it is possible to use m value of **0.017** directly without going through the normal procedure.

And, the factors K_{gm} will normally be set to **1.0** and adjusted only for the road construction and drainage quality factor, k_m, according to Table 5.5.

Accordingly, for non-freezing environment, standard material quality, adequate drainage for local moisture condition, and moderately maintained road, the modifying factor of environmental coefficient for road construction and drainage effect is read to be 1.0 (Table 5.5). Therefore:

$K_{gm} = 1.0 * K_m = 1.0 * 1.0 = \mathbf{1.0}$

2. Otherwise, the software default value determined at level 1 calibration, $m = \mathbf{0.020}$, can be adopted with computed environmental coefficient modifying factor, K_{gm}. Once the observed values of m, **0.017**, have been determined for the representative climate zones, the calibration factor is simply determined as the ratio of observed to the predicted.

$$K_{gm} = \frac{m_{observed}}{m_{default}} = \frac{0.017}{0.020} = \mathbf{0.85} \qquad (16)$$

If the observed values of m differ from the standard values (Table 5.4) by more than half of the difference between m-values for adjacent environmental zones, the assumptions and work of the calibration study should be carefully reviewed to identify possible errors before adopting the observed values. However the difference 0.003 (0.020-0.017) is less than the half difference between of standard m value for tropical semi-arid and tropical sub-humid which is 0.005.

ii. Crack Initiation Adjustment Factor: (Sensitivity Class One, S-I)

Crack initiation is predicted as the surface age when fatigue cracking becomes visible, with a minimum area of 0.5 per cent of the carriageway area (or about 1.8 m of 100 m lane length).

The Level 2 calibration takes account of both the implicit and explicit predictive parameters through direct field observations. Implicit parameters include the material design and climate-related ageing which both affect fatigue behavior. Therefore cracking predictions are calibrated specific to the surfacing type and the climate.

Explicit parameters include pavement structural parameters (such as structural number, deflection, surfacing thickness, etc.) and traffic loading parameters (for example, annual loading (YE4), etc.) - which are measured on the sample pavements.

The HDM-4 crack initiation model forms are separated firstly for stabilized and granular bases and secondly for original surfacing and resurfacing of existing surfaces. Most of the Addis Ababa – Modjo road falls within the granular base and original surfacing categories. Thus the crack initiation for these types of pavements is given by:

$$\mathrm{ICA} = \mathrm{K_{cia}}\left\{\mathrm{CDS}^2 * \mathrm{a}_0 * \exp\left[\mathrm{a}_1 * \mathrm{SNP} + \mathrm{a}_2 * \left(\frac{\mathrm{YE4}}{\mathrm{SNP}^2}\right)\right] + \mathrm{CRT}\right\} \qquad (17)$$

Where:

ICA	time to initiation of all structural cracks (years)
CDS	construction defects indicator for bituminous surfaces (ranges from 0.5 to 1.5, for optimal binder content 1.0)
YE4	annual number of equivalent standard axels (millions/lane), which is equal to 4.06 for the prevailing traffic data, (= NE ESA/pavement age, 12years)
SNP	average annual adjusted structural number of the pavement
K_{cia}	calibration factor for initiation of ALL cracks
CRT	crack retardation time because of maintenance (years) (8 years default)
a_i	model coefficients which is equal a_0=4.21, a_1=0.14, and a_2=-17.1 for Asphalt mix surfacing & granular base course

Crack Initiation Calibration Methodology

For the pavement data record, the predicted all cracking initiation age was calculated by the model relationship using a spreadsheet.

The calibration adjustment factors and prediction errors are determined separately from the mean predicted (mean PTCI) and observed initiation (mean OTCI). The HDM-4 proposed method to calibrate crack initiation models is (Bennett & Paterson 2000):

$$\mathrm{k_{cia}} = \frac{mean\ \mathrm{OTCI}}{mean\ \mathrm{PTCI}} \qquad (18)$$

$$\mathrm{RMSE} = \mathrm{SQRT}\left\{\mathrm{mean}\left[\left(\mathrm{OTCI}_j - \mathrm{PTCI}_j\right)^2\right]_{j=1,n}\right\} \qquad (19)$$

RMSE	root means square error is the error function to minimize
OTCI	observed time to crack initiation
PTCI	predicted time to crack initiation

The Ethiopian Roads Authority Road Condition Report (October 2004 GC) indicates that there is a considerable range of narrow crack areas which is the first crack record of the road observed. Thus, the observed time to crack initiation (mean OTCI), which is the time difference between service opening year (2001 GC) and the first considerable crack area report (late 2004 GC), is 4 years.

By applying the information given so far, the calibration process involves an iterative process using equation 17, 18, and 19. It is performed with Microsoft Excel spreadsheet. The result indicates the value of:

$\mathbf{K_{cia}}$ to be $\mathbf{0.67}$ with corresponding value of PTCI (which is ICA given at equation (17)) **5.93 years** and RMSE of **1.93 years**.

iii. Crack Progression Models: (Sensitivity Class One, S-I)

On each identified cracking calibration pavement section, the following data should be determined and recorded:

1. Surfacing age (years)
2. Percentage area of all cracking (more than 1 mm width)
3. Percentage area of wide cracking (more than 3 mm width or spalled narrow cracks)
4. Values of the explicit independent parameters required for predicting cracking initiation and progression

The above data is collected from Ethiopian Roads Authority Condition Survey Report and shown in Table 5.11.

Table 5.11: All Crack Areas in Percent for Different Years

Measurement	Value
Surface Age (years)	12
All Crack Area Percentage	
Year 2005 GC	6.92
Year 2011 GC	5.33
Year 2012 GC	13.97

The above data is the only available data and the decrease in crack amount from year 2005 to 2011 indicates that there has been a crack sealling activity.

Evaluation

Where crack progression data are available, the following method could be used. For the pavement data record:

1. The predicted cracking initiation age, calculated by the model relationship using a spreadsheet and adjusted by the calibration adjustment factors determined is needed (discused under Section ii)
2. The estimated age since cracking initiation is calculated by subtracting the predicted cracking initiation age from the observed surfacing age
3. Fit a sigmoidal curve to the observed cracking area versus the estimated age since initiation data, and determine the estimated age at 30 per cent cracking area (ET30) by interpolation or extrapolation
4. Calculate the predicted age at 30 per cent cracking area (PT30) using the HDM-4 equation with coefficients appropriate for the pavement and surface type, then:

$$K_{cp} = \frac{PT30mean}{ET30mean} \tag{20}$$

where: K_{cp} is crack progression calibration factor

PT30 is the predicted age at 30% cracking

ET30 is the actual age at 30% cracking

According to this attempt, the calibration of the crack progression model is difficult. Firstly, there is no enough time series data which can be used for the curve fitting and generally no historical data are kept after cracks have been sealed. Secondly, crack sealed quantities are often not kept. However, the crack progression model has a low priority since it has a lower sensitivity than crack initiation and engineering experience has indicated that the actual crack quantity is not very significant compared to the simple information of when a pavement cracks (Henning, et al. 2000).

Alternative Approach

As discusssed above, it is normally problematic to calibrate this model since it takes a long time to collect crack data in an experiment, and crack progression is seldom found on a network given early maintenance intervention. For this reason the HDM-4 guidelines (Bennett & Paterson 2000) recommend a simple alternative approach of:

$$\mathrm{K_{cp}} = \frac{1}{\mathrm{K_{cia}}} = \mathbf{1.49} \qquad (21)$$

where: K_{cp} is the calibration coefficient for crack progression
K_{cia} is the calibration coefficient for crack initiation which equal to **0.67**

iv. Rut Depth Progression Factor: (Sensitivity Class Two/Three, S-II/III)

The rut depth progression factor involves calculation of standard deviation of observed rut depth data in the calibration site. However, due to the reason that there is no enough time series data to perform this calibration, it is not computed here in this paper. Therefore, the default value computed for level 1 calibration is retained useable.

v. General Roughness Progression Factor: (Sensitivity Class Three, S-III)

The roughness progression relationship predicts the change in roughness under the influence of several factors including distress, a Level 2 calibration of K_{gp} requires a time-series of at least four years of reliable roughness data on a wide range of pavement segments.

The HDM-4 advise that it is unusual for this general factor to need adjustment and it is more likely that one of the internal factors need correction; for example, the environmental coefficient (m or kge), structural parameters (SNP or YE4), or the patching and potholing coefficients. And, If adjustment is found to be necessary, then plans should be made to conduct the more rigorous analysis described for a Level 3 adaptation.

Even if the most of the parameters described are calibrated, it is stated that rutting and potholing calibration will not be executed due to incompleteness and/or unavailability of condition data records. On the other hand, the roughness data records relatively are more available in terms of International roughness index (IRI) and the calibration factor serves a good check for the calibration job. For these reasons, the general roughness progression factor calibration is performed here in.

Evaluation

Acording to the HDM-4's Calibration and Adoption Guide, the observed incremental values are determined by computing the difference between the averages of the first and last pairs of values, adjusted to the full applicable period by extrapolation, and the mean values by arithmetic averaging:

$$\Delta\mathrm{ORI} = \left\{\frac{[\mathrm{AVG(ORI3,ORI4)-AVG(ORI1,ORI2](OT4-OT1)}}{[\mathrm{AVG(OT3,OT4)-AVG(OT1,OT2)}]}\right\} \quad (22)$$

Where:		
	$\Delta\mathrm{ORI}$	is the roughness incrimental value [m/km]
	$\mathrm{ORI4}$	is the observed rghoughness at the t=4th and
	$\mathrm{OT4}$	is the corrosponding time in years of the t=4th observation

$$\mathrm{MORI} = \frac{\mathrm{SUM(ORI1{:}ORIn)}}{\mathrm{n}} \quad (23)$$

Where:		
	MORI	is mean of observed roughness
	ORI	is observed roughness

Table 5.12: The Average Observed Roughness Values (partial data given in Appendix B)

Year (GC)	Roughness, IRI (m/km)
2010	2.19
2011	2.50
2012	3.10
2013	3.17

$$\therefore \Delta\mathrm{ORI} = \left\{\frac{\big(0.5*(3.10+3.17)-0.5*(2.19+2.5)\big)*(2013-2010)}{0.5*(2012+2013)-0.5*(2010+2011)}\right\} = \mathbf{1.185}$$

$$\mathrm{MORI} = \frac{2.19+2.50+3.10+3.17}{4} = \mathbf{2.74}$$

The unadjusted predicted value of incremental roughness (ΔPRIt) is calculated for the calibration segment using the primary prediction.

$$\Delta\mathrm{PRI} = \mathrm{a_0}\exp\big(\mathrm{mK_{gm}AGE3}\big)\,(1+\mathrm{SNPk_b})^{-5} * \mathrm{YE4} \quad (24)$$

Where:

ΔPRI	incremental change in roughness during the analysis year (IRI m/km)
a_0	coefficient, 134 (Bennett, 2000)
m	environmental coefficient, 0.017 (computed in section i.)
K_{gm}	calibration factor for environmental coefficient, 1.00 (section i.)
AGE3	pavement age since last overlay, 12years
$SNPK_b$	adjusted structural number of pavment due to cracking at the end of the analysis year, 2.5 (default value)
YE4	annual number of equivalent standard axels, 4.06 (discussed in seciton ii.)

$$\Delta\mathrm{PRI} = 134 * \exp(0.017 * 1.00 * 12)\,(1+2.5)^{-5} * 4.06 = \mathbf{1.270}$$

Then, the residual error of the observed and predicted values of roughness increment is computed as:

$$\mathrm{RESRI} = \Delta\mathrm{PRI} - \Delta\mathrm{ORI} = 1.270 - 1.185 = \mathbf{0.085}$$

The slope between the RESRI and MORI,

$$b = \frac{\mathrm{RESRI}}{\mathrm{MORI}} = \frac{0.085}{2.74} = \mathbf{0.031} \qquad (25)$$

Therefore, the adjustment factor will be:

$$K_{gp} = 1 + b = \mathbf{1.031} \approx \mathbf{1.03} \qquad (26)$$

5.2 Result Discussion

Based on the calibration models previously described, calibration factors for the various pavement deterioration and environmental effect on the calibration pavement were obtained applying the HDM-4 Calibration and Adoption technique for each category.

For the calibration pavement section consisting of asphalt surfacing, granular base and sub – base, the environmental coefficient value has decreased from 0.0200 (level 1 calibration) to 0.017(level 2 calibration) implying a lesser annual roughness increment due to environmental on the pavement than normally suggested in basic calibration.

However, the structural cracking initiation adjustment factor (K_{cia}) evaluated value is below 1.00 (which is 0.67) unlike the progression factor (K_{cp}) , exceeding 1.00 (1.49). This infers that, cracks generally appear earlier than predicted by the basic non-calibrated HDM-4 crack initiation models. Moreover, the crack progression observed in the calibration site is faster than the one determined by non-calibrated HDM-4 models.

The actual fatigue cracking appears prematurely due to the reason that Addis Ababa – Modjo is one of the most traversed major trunk roads in Ethiopia (Appendix B).

The disadvantage of these HDM-4 crack simulation approaches is that, it only takes in to account sections that are cracked, thus generally disregards sections which outlast expected performance. This method will therefore be biased towards early cracked sections rather than pavements which are strong and without cracks.

The general roughness progression factor (K_{gp}) is also calibrated and its result was slightly greater than 1.00 (which is 1.03). This result does not indicate a similarity in forecasted and observed roughness magnitudes. However, it shows execution of this calibration factor is not necessary if environment – age – roughness factor, crack initiation and progression, patching and potholing coefficients are performed. And yet, it is included here because the last two performance calibration (rutting and potholing) are not done and for checking purposes. Therefore, the factor implements a 3% amplification of predicted incremental roughness magnitude with respect to the observed values.

Moreover, the HMD-4 roughness model format was developed with the underlying philosophy that roughness will always increase incrementally, regardless of how lightly the pavement is loaded or how minor the environmental effects may be.

However, this trend could not be supported by the actual data (partial data is given in Appendix B). Figure 7.1 and 7.2 illustrates the distribution of incremental roughness change between the three surveys (Ethiopian Roads Authority condition data for 2010, 2011, and 2012 GC).

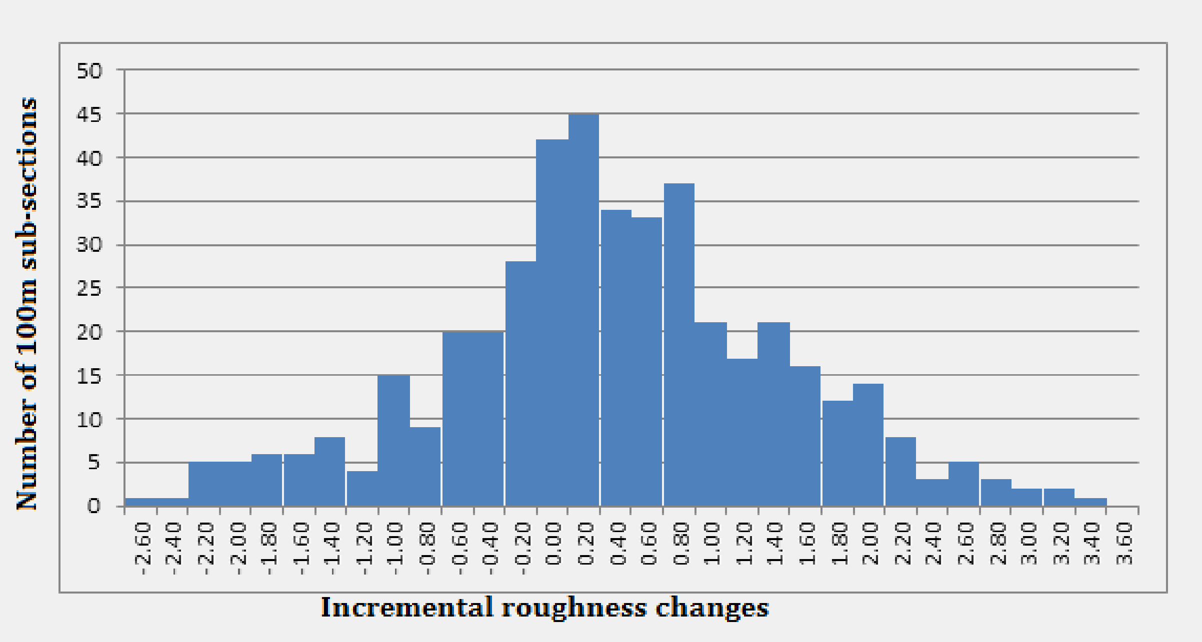

Figure 7.1: Distribution of Roughness Increments between 2010 GC and 2011 GC Survey Years

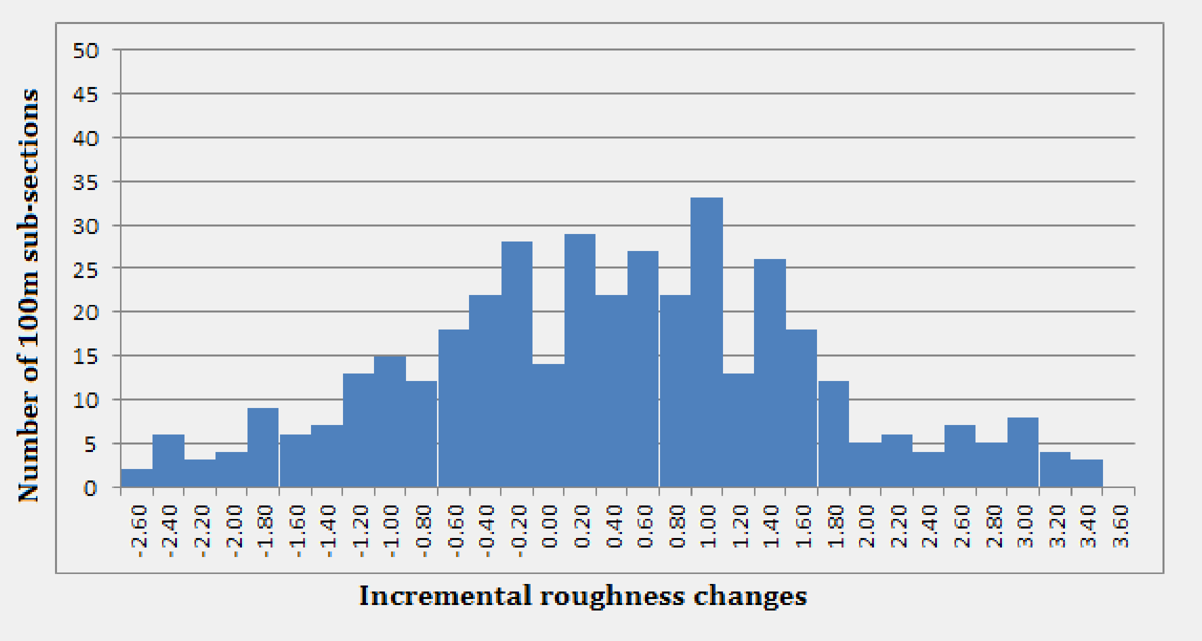

Figure 7.2: Distribution of Roughness Increments between 2011GC and 2012GC Survey Years

It is further noted that the distribution of the roughness change between the 2010 and 2011 survey rounds is wider than between the 2011 and 2010 survey rounds.

Many of the negative changes (i.e. roughness improvements) for the 2010 to 2011 survey periods could be explained by **texture loss** on newly resurfaced roads, and **flushing** on older pavements. These effects were less pronounced in the 2011 to 2012 survey rounds because of less resurfacing in that period. However, given that the accuracy of the roughness measurements is specified at ± 0.2 IRI (Transit 2001, Henning et al. 2004a), any measurements within this tolerance do not necessarily indicate a trend towards improvement or deterioration.

Evidently, the result of this paper shows that project costs estimated by un-calibrated software are considerably underestimated by the crack models. This is because as per the un-calibrated model crack is supposed to be appearing at the 6th year after opening for service, which is the time to begin crack sealing maintenance. Apparently, the pavement exhibits considerable cracks at the 4th year requiring crack sealing mitigation 2 years earlier than estimated. Therefore, the delay of maintenance work will encourage further progression of pavement deterioration. As the crack progression calibration factor shows, the amount of cracked pavement area observed at a particular pavement age is 149% higher than the un-calibrated software prediction. In monetary terms, for instance, if the un-calibrated model estimates 1 million ETB crack sealing cost, you will be shorthanded with 0.49 million ETB because what you actually needed is 1.49 million ETB to complete the task. In addition, the general roughness calibration factor supports this conclusion by suggesting that the overall roughness prediction (including roughness due to rutting and potholing) should be raised by 3% so that it suits the site condition.

On the other hand, the roughness due to environment condition, which is represented by the Roughness – Age – Environment adjustment factor, overestimates the project cost. Observed roughness progression due to environment are generally 15% lower than the model predictions. Care should be taken here that not to get the two deductions by them mixed up and confused. It is obvious that by the nature of the subjects all pavement deteriorations are inter-related and cracking, rutting, potholing and raveling contribute to roughness. This indicates higher cracking progression should result in higher roughness. However, firstly the Roughness – Age – Environment models targeted only the roughness caused by environment, secondly, here in calibration process only the model prediction and the actual observations are considered so the accuracy and relationships of each model is still in need of performing Adoption.

6. Conclusion and Recommendation

This research was aimed at calibration of the roughness and crack simulation models of HDM-4 software. Applying the standard calibration procedure outlined in HDM-4 documentation, the result showed that the magnitude of roughness increment observed is lower than the software's prediction, with K_{gm} = **0.85**. Also, the pavement cracks initiate earlier and progress faster than the one estimated by non – calibrated models, K_{cia}=**0.67** & K_{gp}=**1.49** respectively. Moreover, the general roughness progression adjustment factor, K_{gp}, turns out to be **1.03 ≈ 1.00**. Since the general roughness is a cumulative effect of other distress types, the result indicates that it needs no calibration if the other parameters are already adjusted.

The methodology suggested in this study can be replicated for calibration of HDM-4 pavement deterioration models for paved roads at the country level. In addition to that, for those who are interested to study the HDM-4's present calibration guidelines and underlying model relationships, it clearly notifies discrepancies and area of interest for more profound researches.

Likewise, the calibration factor of pavement roughness and crack models can readily be applied for running the HDM-4 for bituminous pavements in similar climatic region. Thus, any agency or individual can adopt these factors so that the analysis will result in more accurate outputs for the case of Ethiopia. This is valuable especially for feasibility study analysis and in deciding optimal maintenance management strategies for vast road network under constrained budget scenario.

This paper has also stated the discrepancy on recording and maintaining data. This is a major factor influencing the extent of examinations and research papers not to dig more on the subject matter (calibration). Therefore, it is recommended to establish Long Term Pavement Performance (LTPP) recording sites on both major Trunk and Local roads all over the country (Ethiopia). Then, even if it is difficult to put a time frame on the required survey duration, but the period of at least five years distress data record is needed for best correlation and calibration result (Henning et al. 2000).

7. Future Work

Data

This report has demonstrated that the level of data collection accuracy is appropriate for calibration and pavement model development. However, the condition data is incomplete in both type and extent. This has a significant effect on some intuitive trends models (such as roughness) demanding appropriate level of data accuracy existed. Thus, it should be emphasized on the need for further work in pavement data base management in Ethiopia.

Moreover, it is very important that Long Term Pavement Performance (LTPP) monitoring sites being established at different representative climatic regions of Ethiopia. This will enable 1) to perform nationwide calibration and 2) to perform the final (Level 3) calibration (Adoption), which will be applicable for the whole country.

Furthermore, it should be highlighted on the significance of the rapid failure stages of pavement deterioration modeling. This is to understand the behavior of pavement during rapid deterioration better.

Calibration Task

The HDM-4 calibration guide generally uses mean values of model parameters to model pavement deterioration and environmental effects for the whole link (network). However, the Section-based Calibration approach has the advantages of precise calibration and flexible application to each section, as well as matrix and network level analyses. Since each section (or In fact, the best way for checking the precision of the estimation matrix, network) has a unique calibration coefficient set, it is suitable for project-level analysis. In addition, this method can be easily applied by using the minimum data, which consists of just one or two inspection points. By applying the Section-based approach, HDM-4 user can solve the problems related to the deterioration speed and incomplete data.

The Multi – Function (MF) model was proposed to address the problem of a fixed estimation function (Daeseok et al. 2012). This approach is useful when a section has no more than two inspection points. That means this new approach can be used for sections which lack time series pavement condition data. And, it involves fitting more than one curves to simulate the pavement deterioration trend from the last time of maintenance work data to the latest points. Besides, since the concept of the Multi – Function model can be extended to a section, a matrix, and even a network; each section can have a different type of estimation function. This will be very useful for determining the deterioration characteristics in detail.

Additional issues which should be considered in future works include:

1. Comprehensive sensitivity analysis of all the parameters to all the key output variables is needed, particularly for Ethiopian road classes and for all representative vehicle types, so as to classify parameters to sensitivity classes, and finally using the results of the sensitivity analysis work plan for improvement of quality of each and every input data and calibration factor
2. Examination of HDM-4 and its documentation
3. Establishment of research programs for Adaptation (level 3 calibration) of the software for Ethiopia

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APPENDIX A Proposal

Abstract

The Highway Development and Management Tools collectively referred to as HDM-4, developed by the World Bank, incorporates three dedicated applications tools. Namely, project level analysis, road work programming under constrained budgets, and strategic planning of long term network performance and expenditure needs.

Given calibrated, this model is universally applicable. And it has been adopted by many countries in the tropic and all over the world. However, to be effective it requires regional adjustment as per the prevailing condition of the region.

Our country, Ethiopia, is one of the countries using this software for project level analysis, especially for feasibility analyses, and pavement management purposes. So it is noteworthy to ask a question, “How dependable the software outputs are?” In addition to that, there has not been a proper calibration and validation of the software so far, rather there is a general tendency to adopt default software values. These reasons derive and motivate this research to be conducted.

HDM-4 can be calibrated for two general categories, Road User Effect and Road Performance Models. However, this study will focus on Road Performance Models calibrations. These models control the processes of initiation and progression of pavement distress which has direct influence on economic evaluation of the road network being analyzed, like current or future maintenance budget allocation, strategic planning and etc.

Introduction

The Highway Development and Management Tools, HDM-4, is the successor to the World Bank Highway Design and Maintenance Standards Model (HDM-III), which incorporates three dedicated applications tools. These are project level analysis, road work programming under constrained budgets, and strategic planning of long term network performance and expenditure needs.

The Highway Development and Management-4 (HDM-4) model is universally applicable; and it has been adopted by many countries in the tropic (Chai et.al, 2004). Of course it has a universally applicability; but to be effective it requires regional calibration as per the prevailing condition of the region. To ensure local accuracy, 36 calibration sections have been set up in 1993 (Rohde et al, 1993). The model simulates physical and economic conditions over the period of analysis and the results are presented in the Long Term Rolling Programme (LTRP) report. The essential part of the LTRP includes the forecasted budget allocation. However, adequate budget allocation would require the HDM-4 model to generate good prediction of the actual pavement deterioration behaviour (Chai et.al, 2004).

Local adaptation and calibration of HDM-4 models can be achieved by specifying default data sets that represent pavement performance and vehicle resource consumption in the country where the model is being used. The need for a calibration of the HDM-4 model to local condition is therefore essential component of the pavement management process.

Problem Statement

Our country, Ethiopia, is one of the countries using this software for project level analysis, especially for feasibility analysis, and pavement management purposes. So it is noteworthy to ask a question “how dependable the software outputs are?”

The degree of HDM-4’s accuracy mainly depends on the data input. That is, the input data accuracy and correct interpretation; the experience and precision of data collection personnel; method and tools used for data collection; and even technique organization data organization. In addition to that, “how software’s analysis models can really model or represent what is going on and what will happen to the local road?” does matter the software’s whole deduction and prediction about road. Generally, “how believable the outputs of HDM-4 are?” depend on accuracy and reliability of input data, level of calibration, and a careful checking up of outputs with good judgement (Kerali, 2008).

This leads to a need for a proper calibration of the software’s models according to actual recorded data of the location at which it is going to be applied. Fail to calibrate the model at all or improper model calibration, result the actual pavement deterioration trend and the HDM-4 predicted deterioration to show large differences. And analysis will evidently result in misleading defaulted outputs which in turn lead to defective conclusions and decisions.

Ethiopian Road Authority (ERA) as the one responsible for administrating most of our country’s highways, there has not been a proper calibration and validation of the software rather there is a tendency to adopt default software values so far. This reason has motivated to conduct this research.

Literature Review

Different countries around the world have been using and calibrating the software, HDM-4. Austroads National Strategic Research Plan has tried to set up accelerated loading facility under controlled maintenance and environmental condition, eight long term pavement maintenance monitored sites, and five sealed granular pavements from 21 long term pavement performance monitored sites to record pavement performance data. Using the above, they deduce the relative effect of maintenance on performance, estimate of actual rates of deterioration experienced the long term pavement performance sites under varying condition of maintenance, environmental conditions, and loading conditions. (Martine, 2004)

The HDM-4 predictive relationships have been applied in many developed and developing countries having markedly different technology, climatic and economic environments. The field experiments covered wide ranges of conditions, there remain some local factors that could not be introduced into the model because they would have made the model's input too complex or their effects could not be determined within the ranges observed (Bennett and Paterson, 2000). For these reasons, calibration of the HDM-4 model to local conditions is necessary and recommended. Moreover, if calibration is not carried out the actual pavement deterioration trend and the HDM-4 predicted deterioration may show large differences. Thus, inadequate local calibration can under or overestimates the budget allocation of highway expenditure (Chai et.al, 2004).

Chai and Gray have also calibrated the model for North South Expressway of Malaysia. The have set up long term pavement performance (LTPP) recording sites to record pavement performance data. This data was compared with HDM-4's outputs and they have made necessary adjustments to the calibration factors to make its predictions reasonable. Also they have use regression analysis and iteration methods for calibration purposes. Therefore, the parameters of calibration are estimated directly from the HDM-4 predictive model for roughness progression as follows:

1. First, estimate the initial roughness for each LTPP calibration site after plotting the best-fit progression curve based upon the measured roughness values.
2. Using the initial roughness values, determine the predicted roughness progression using HDM-4 default value of 1 and plot the curves for each LTTP site on the same graphs as the measured roughness.
3. Modify the calibration factor through an iterative process for each LTPP site until the predicted roughness progression curves come as close as possible to the measured roughness progression curves.
4. Adopt the above derived calibration factors as the Level 2 calibration factors for roughness age- environment component of the roughness progression model.

Objective

The main objective of this study is to calibrate HDM-4 model. The location selected for analysis is Addis – Mojo link due to better pavement performance recorded data. HDM-4 can be calibrated for two general categories, Road User Effect and Road Performance Models. However, this study will focus on Road Performance models calibrations.

Road Performance Models model the processes of initiation and progression of pavement distress which has direct influence on economic evaluation of the road, like current level of performance, current or future maintenance budget allocation, strategic planning and etc. Thus an accurate pavement performance models outputs makes it necessary to adequately adjust or calibrate the model because it has a very important economic impact.

Specific Objective

- Identifying HDM-4's pavement performance models which have sufficient data for calibration
- Calibrate HDM-4 Program for Addis – Mojo road sections for road performance models;

Methodology

The first step will be to review the extent of application of HDM-4 in Ethiopia. By this step the constructive practices and possible gaps in the software will be discussed.

The next step will be to identify pavement performance models types which have adequate data to be calibrated.

In data collection process the total length of the road, which is constructed with flexible pavement, will be divided in to segments according to the prevailing climatic condition, traffic, method and material type of construction, and pavement age. If there are considerable differences in the above criteria, the road under study will be divided into sections of similar weather, traffic, pavement type, and pavement conditions. Therefore, there will be grading of the construction material quality classification and designation as high, good, fair, poor etc. accordingly; which is true of other criteria.

The HDM-4 model simulates future changes to the road system from current condition and basically the application of the model involves two important steps:

Data Input – Data input needs correct interpretation of the data input requirements, and achieving a quality of input data that is appropriate to the desired reliability of the results.

Calibration of outputs – Adjusting the model parameters to enhance how well the forecast and outputs represent the changes and influences over time and under various interventions.

Essentially, there are three levels of calibration for the HDM-4 calibration. The three calibration levels involving low, moderate and major levels of effort and resource are as follows:

- Level 1 – Basic Application
  This level involves a desk study and many default values will be adopted and the most sensitive parameters will be calibrated using the guidelines given in the HDM-4 manual.
- Level 2 – Main Calibration
  This level of calibration will be accomplished for the parameters with quality historical data (e.g. roughness, cracking and rutting). Field survey will be carried out to measure additional pavement parameters in order for key predictive relationships to be calibrated to local condition.
- Level 3 – Adaptation
  It undertakes major field surveys and controlled experiments at LTPP sites to enhance the existing predictive relationships.

Since Level 3 calibration involves years of study and data collection, which is a major constraint of this thesis, the calibrations dealt with this paper are Level 1 and Level 2. Level
2 calibration will be carried out for those parameters with high and low impact on deterioration and for which time series data is available.

Calibration of HDM-4 encompasses running the software with the default values of the software and comparing predictive outputs of pavement distresses by the software package with the actual observed field data. Then if there are major discrepancies, necessary adjustment will be made by tuning up the software's parameters until the predictions and the observed data are reasonably similar.

Application of Result

The outputs of this thesis are calibration factors representing different pavement phenomenon. These factors can be applied to run HDM-4 software for more accurate results. Model's prediction result will fits well to the real behaviour of the road section under study.

In addition to that, calibrated model factors can be applied for other road links having similar traffic, environment, pavement material, and construction standards.

In addition to that, this research can be a good start for further researches on calibrating HDM-4 and related issues.

APPENDIX B Partial Pavement Condition Data

Pavement cracking

2012GC						
From (km)	**To (km)**	**Altitude (m)**	**Lane_1 Cracks Wide (m2)**	**Lane_2 Cracks Wide (m2)**	**Lane_1 Cracks Narrow (m2)**	**Lane_2 Cracks Narrow (m2)**
0	0.1	2102.2	0.00	0.00	0.00	0.00
0.1	0.2	2101.5	0.00	0.00	0.00	0.00
0.2	0.3	2100.8	0.00	0.00	0.00	0.00
0.3	0.4	2100.3	0.00	0.00	0.00	98.85
0.4	0.5	2099.4	0.00	0.00	0.00	0.76
0.5	0.6	2099	0.00	0.00	0.00	16.09
0.6	0.7	2099	0.00	19.66	0.00	23.04
0.7	0.8	2098.5	0.00	0.00	0.00	0.00
0.8	0.9	2098.2	0.00	0.00	0.00	0.00
0.9	1	2096.9	24.44	2.86	0.00	9.01
1	1.1	2095.5	40.21	0.00	0.00	6.72
1.1	1.2	2094.9	49.65	4.38	0.34	63.99
1.2	1.3	2095	34.90	1.92	0.00	91.36
1.3	1.4	2097.5	6.06	85.82	0.00	142.19
1.4	1.5	2100.7	0.00	0.00	0.00	69.46
1.5	1.6	2104.8	0.00	0.00	0.00	0.34
1.6	1.7	2109.4	0.00	0.00	0.00	0.00
1.7	1.8	2113.3	0.00	0.00	0.00	0.00
1.8	1.9	2116.8	0.00	0.00	0.00	0.00
1.9	2	2121.2	3.36	0.00	0.00	0.00
2	2.1	2125.1	0.00	27.37	0.00	174.51
2.1	2.2	2129.8	0.00	0.55	0.00	225.63
2.2	2.3	2133.9	0.00	89.40	0.00	67.73
2.3	2.4	2138.4	77.61	0.00	0.00	13.24
2.4	2.5	2141.6	321.69	28.08	2.86	15.56
2.5	2.6	2143	181.55	0.00	24.70	66.98
2.6	2.7	2143.9	27.56	0.00	10.29	15.71
2.7	2.8	2143.9	0.00	0.00	0.00	1.30
2.8	2.9	2145.2	0.00	0.00	0.00	8.23
2.9	3	2147.4	0.00	12.40	0.00	36.00
3	3.1	2148.9	0.00	3.56	0.00	18.98
3.1	3.2	2150.1	0.00	0.00	0.00	0.00
3.2	3.3	2150.1	9.48	0.00	0.00	0.00

Continued

From (km)	To (km)	Altitude (m)	Lane_1 Cracks Wide (m2)	Lane_2 Cracks Wide (m2)	Lane_1 Cracks Narrow (m2)	Lane_2 Cracks Narrow (m2)
3.3	3.4	2151	8.83	0.00	1.56	0.00
3.4	3.5	2152.1	12.81	0.00	0.00	0.00
3.5	3.6	2154	0.00	0.00	0.00	0.00
3.6	3.7	2155.7	0.00	0.00	0.00	0.00
3.7	3.8	2156	44.45	0.00	0.00	0.00
3.8	3.9	2155.2	0.00	0.00	2.76	57.31
3.9	4	2153.5	160.46	0.00	0.37	70.03
4	4.1	2150.9	63.06	0.00	0.00	53.28
4.1	4.2	2146.2	2.92	0.00	0.00	62.42
4.2	4.3	2143.3	0.00	0.00	0.00	24.31
4.3	4.4	2141.7	0.00	0.00	4.23	4.05
4.4	4.5	2139.3	10.45	0.00	6.79	0.32
4.5	4.6	2137.8	18.44	0.00	0.00	0.00
4.6	4.7	2137	8.49	0.00	21.95	0.00
4.7	4.8	2135.2	66.72	0.00	41.01	0.00
4.8	4.9	2132.9	5.73	0.00	8.77	0.00
4.9	5	2131.4	0.00	0.00	0.71	6.28
5	5.1	2129.5	4.70	0.00	2.78	81.06
5.1	5.2	2127.6	9.42	0.00	0.23	28.28
5.2	5.3	2125.7	23.53	0.00	0.58	41.91
5.3	5.4	2124.3	12.21	0.00	6.18	180.03
5.4	5.5	2122.5	167.03	0.00	36.15	22.43
5.5	5.6	2119.4	40.91	0.00	38.46	27.80
5.6	5.7	2116.6	111.09	0.00	1.06	0.00
5.7	5.8	2114.2	194.65	0.00	2.04	9.29
5.8	5.9	2112.3	86.70	0.00	0.00	47.79
5.9	6	2111.2	1.99	0.00	0.00	43.20
6	6.1	2109.5	83.35	0.00	24.40	56.67
6.1	6.2	2107.7	0.00	0.00	0.00	47.70
6.2	6.3	2106.6	0.00	0.00	0.00	6.18
6.3	6.4	2106.2	0.00	0.00	0.00	2.94
6.4	6.5	2107.4	4.58	0.00	0.00	45.30

Pavement roughness

2011

				Increment	
Distance (km)	**Roughness _2010**	**Roughness _2011**	**Roughness _2012**	**2011GC - 2010GC**	**2012GC - 2011GC**
0.1	1.50	2.94	3.39	1.44	0.45
0.2	1.88	2.14	3.66	0.26	1.52
0.3	3.45	1.53	1.98	-1.92	0.45
0.4	2.81	1.06	2.57	-1.75	1.51
0.5	3.93	1.71	3.16	-2.22	1.45
0.6	2.38	2.99	2.20	0.61	-0.79
0.7	1.51	1.38	2.65	-0.13	1.27
0.8	3.25	2.21	1.92	-1.04	-0.29
0.9	3.38	1.79	3.15	-1.59	1.36
1	2.60	2.30	3.88	-0.30	1.58
1.1	1.94	2.27	3.28	0.33	1.01
1.2	2.68	2.15	2.86	-0.53	0.71
1.3	2.73	2.39	4.14	-0.34	1.75
1.4	1.88	4.49	3.24	2.61	-1.25
1.5	2.31	3.64	3.83	1.33	0.19
1.6	2.00	2.60	3.06	0.60	0.46
1.7	2.44	4.20	3.06	1.76	-1.14
1.8	2.11	2.60	3.06	0.49	0.46
1.9	2.55	2.77	3.65	0.22	0.88
2	2.43	2.56	4.23	0.13	1.67
2.1	2.88	2.59	3.94	-0.29	1.35
2.2	2.44	3.24	4.08	0.80	0.84
2.3	2.50	3.25	3.30	0.75	0.05
2.4	1.60	2.98	2.52	1.38	-0.46
2.5	1.51	1.48	4.82	-0.03	3.34
2.6	1.45	1.88	3.88	0.43	2.00
2.7	1.37	2.56	2.32	1.19	-0.24
2.8	1.49	2.85	2.24	1.36	-0.61
2.9	1.08	3.89	1.77	2.81	-2.12
3	1.15	4.83	2.57	3.68	-2.26
3.1	1.63	2.74	2.05	1.11	-0.69
3.2	1.43	2.92	2.50	1.49	-0.42
3.3	1.35	3.45	2.80	2.10	-0.65
3.4	1.42	2.42	3.73	1.00	1.31

APPENDIX C Partial Traffic Data

Traffic Year 2002	Route Name	ADDIS ABABA - KALITY	KALITY - D/ZEYIT	D/ZEYIT - NAZRATH
	Length	15	32	51
	Cars	1,624	1,049	673
	Land Rovers	2,115	1,404	969
	Small Buses	2,249	649	833
	Large Buses	1,259	621	576
	Small Trucks	1,359	485	719
	Medium Trucks	1,497	1,017	843
	Heavy Trucks	1,526	1,283	880
	Truck Trailers	1,210	892	1,028
	Total	12,839	7,400	6,521
Traffic Year 2003	**Route Name**	ADDIS ABABA - KALITY	KALITY - D/ZEYIT	D/ZEYIT - NAZRATH
	Length	15	32	51
	Cars	1,632	1,313	639
	Land Rovers	2,194	1,688	935
	Small Buses	2,104	869	770
	Large Buses	1,343	759	506
	Small Trucks	1,349	530	715
	Medium Trucks	1,948	1,327	732
	Heavy Trucks	1,786	1,391	763
	Truck Trailers	1,709	957	1,000
	Total	14,065	8,834	6,060
Traffic Year 2004	**Route Name**	ADDIS ABABA - KALITY	KALITY - D/ZEYIT	D/ZEYIT - NAZRATH
	Length	15	32	51
	Cars	1,944	1,408	598
	Land Rovers	2,719	1,800	970
	Small Buses	2,832	972	739
	Large Buses	1,686	811	439
	Small Trucks	1,673	476	730
	Medium Trucks	2,132	1,508	668
	Heavy Trucks	2,255	1,419	695
	Truck Trailers	1,894	1,159	891
	Total	7,135	9,553	5,730

Continued

Traffic Year 2005	**Route Name**	ADDIS ABABA - KALITY	KALITY - D/ZEYIT	D/ZEYIT - NAZRATH
	Length	15	32	51
	Cars	2,286	1,316	760
	Land Rovers	2,962	1,630	1,213
	Small Buses	2,814	1,288	958
	Large Buses	2,134	1,145	519
	Small Trucks	2,741	1,006	631
	Medium Trucks	2,982	1,774	1,051
	Heavy Trucks	2,910	1,581	930
	Truck Trailers	2,965	1,634	1,214
	Total	21,794	11,374	7,276
Traffic Year 2006	**Route Name**	ADDIS ABABA - KALITY	KALITY - D/ZEYIT	D/ZEYIT - NAZRATH
	Length	15	32	51
	Cars	3,518	1,451	705
	Land Rovers	3,947	1,744	1,113
	Small Buses	4,481	1,804	990
	Large Buses	2,170	1,125	664
	Small Trucks	2,615	1,572	746
	Medium Trucks	3,436	1,833	1,023
	Heavy Trucks	3,171	1,632	1,014
	Truck Trailers	3,266	1,697	1,183
	Total	26,604	12,858	7,438
Traffic Year 2007	**Route Name**	ADDIS ABABA - KALITY	KALITY - D/ZEYIT	D/ZEYIT - NAZRATH
	Length	15	32	51
	Cars	4,029	1,903	1,084
	Land Rovers	4,844	2,193	1,353
	Small Buses	5,300	2,014	1,432
	Large Buses	2,440	1,427	970
	Small Trucks	3,445	997	1,069
	Medium Trucks	4,020	2,070	1,503
	Heavy Trucks	3,699	1,585	1,547
	Truck Trailers	3,998	2,472	1,738
	Total	31,775	14,661	10,696