SENSITIVITY ANALYSIS OF HDM4 TOOL USING A CASE STUDY

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The author hereby declares that this thesis entitled **"Sensitivity Analysis of HDM 4 Tool Using A Case Study"**, in whole or part, has not been used to obtain any degree in this, or any other, institute. Except where references have been given in text, it is entirely the authors own work. The author confirms that the library may lend or copy this thesis upon request for academic purposes.

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ABSTRACT

Pavements which are left to deteriorate without timely maintenance treatment are likely to require major rehabilitation and reconstruction much sooner than those which are properly maintained. In developing countries like India, where the traffic growth and axle loading is growing at logarithmic scale, deterioration of highways is very fast. The objective of this study is to find the sensitivity of using un-calibrated and calibrated inbuilt distress models of HDM-4 Tool using the above said case study. The sensitivity has been done using HDM-4 software for project analysis. The HDM-4 tool provides the deterministic approach in data input and processing also utilizes data on existing road condition, traffic volume and crust composition to predict road deterioration as per the road conditions in terms of any one variable such as International Roughness Index (IRI). HDM-4 simulates the best alternative that need to be applied based on Economic Internal Rate of Return (EIRR) which consist Total Transportation Cost (TTC), Vehicle Operating Cost (VOC), roughness pattern. After performing normal project analysis and selecting the best fit alternative for the section, calibration factor for crack initiation and crack progression are changed one by one and corresponding Economic Internal Rate of Return, Total Transportation cost, Average Vehicle Operating Cost, Average Travel Time Cost, Average Road User Cost, Cracking pattens, roughness patterns are compared. A road network economic evaluation is the most challenging use of the model, but the effort is well justified due to the potential savings on transportation costs achieved by comparing various alternatives. This thesis presents the concept for using calibrated models of HDM-4 for analysis, reviews the applied methodology, input requirements and also shows future directions in order to apply HDM-4 effectively. The methodology described here in attempts to take advantage of all the capabilities of HDM-4, deal with the limitations of HDM-4, and produce usable results. It is important that the selected road works per road class be feasible from a purely technical point of view to produce realistic results.

LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
ARSS	Automated Road Survey System
AASHTO	American Association Of State Highway and Transportation Officials
BC	Bituminous Concrete
DBM	Dense Bituminous Macadam
D_c	Characteristics Deflection
DSR	Departmental Scheduled Rates
EIRR	Economic Internal Rate Of Return
HV	Hourly Volume
HDM-4	Highway Development Management Tool-4
IAPMS	Integrated Airport Pavement Management System
ISOHDM	International Study of Highway Development and Management
IRI	International Roughness Index
LVR	Low Volume Roads
M & R	Maintenance and Rehabilitation
MMR	Mumbai Metropolitan Region
MT	Motorized Traffic
NH	National Highway
NMT	Non-Motorized Traffic
PMS	Pavement Management System
PSI	Present Serviceability Index
PCNADT	Percentage Of Average Daily Traffic
RDWE	Road Deterioration and Work Effects
RUE	Road User Cost
SDBC	Semi Dense Bituminous Macadam
VOC	Vehicle Operating Effects

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CHAPTER 1

INTRODUCTION

1.1 Indian Road Network

India is said to be the fastest developing countries today only after China. India in its past did not allocate enough resources to build or maintain its road network. Although India is doing exceptionally well in different field but there are still certain areas where the country is lagging behind. This has changed since 1995, with major effects currently underway to modernize the country's road infrastructure. India has a road network of over 46.9 lakh km of roads, the second largest road network in the world. It is a well-known fact that a good roadway network has a strong and positive relationship with the national economy.

India's road network is gigantic and said to be only after the United States of America. But one of the striking underlying facts is the condition of the roads. Since roads indirectly contribute to the economic growth of the country it is extremely essential that the roads are well laid out and strong. Bad road conditions are not new to India and this problem is still being addressed since last 30 years. The other problems faced by the Indian roads are bad riding quality, poor geometrics, and insufficient pavement thickness.

Without timely maintenance, roads deteriorate considerably, leading to higher vehicle operating costs (VOC), increased number of accidents and reduced reliability of transport services. When the maintenance work can no longer be delayed, it will often involve extensive rehabilitation, and even reconstruction, costing many times more than timely maintenance treatment carried out earlier. Late or inadequate maintenance will increase the ultimate repair costs, road user costs and inconvenience to road users, and reduce safety. Road maintenance is therefore an essential function and should be carried out on a timely basis.

The importance of preserving an adequate condition of the road network is widely recognized. Although, developing and maintaining a good road network is not an easy task. It requires meticulous planning, enormous funds, challenging construction techniques, strict quality control and other related aspects. Road networks need to be managed now and not just maintained.

1.2 Concept of Pavement Maintenance Management Practices

Pavement is considered as the upper part of the road structure and includes all layers resting on subgrade. The purpose of pavement is to serve traffic safely, comfortably, and efficiently at minimum or reasonable cost. Pavements deteriorate gradually over a period of time as a function of material quality, structural design, and traffic loading and environmental details. It is difficult to predict the deterioration of pavement. The answer to the question of need of Pavement Management System (PMS) is as follows:

- Road system deficient to meet the traffic demand
- Improper Planning
- Deficiencies in Road Geometrics
- Poor Construction and Maintenance
- Need for Proper Planning and Management of Resources
- Pavements fails pre-maturely because of
    - Improper design
    - Poor Construction practices
    - Poor Drainage Maintenance
    - Frequent cutting

Pavement Management is the effective and efficient directing of the various activities involved in providing and sustaining pavement in a condition acceptable to the travelling public at the least life cycle cost. These activities include:

a) Planning

b) Budgeting and programming
c) Design
d) Construction
e) Monitoring
f) Research
g) Maintenance
h) Rehabilitation
i) Reconstruction

Pavement Management System is an established, documented procedure treating many or all of the Pavement Management activities in a systematic and coordinated manner. It consists of six essential elements structured to help decision makers at various management levels. These elements are:

a) Pavement surveys related to condition and serviceability
b) Data base containing all pavement related information
c) Analysis scheme
d) Decision Criteria
e) Implementation procedures
f) Feed back

A Pavement Management System is a set of defined procedures for collecting, analyzing, maintaining, and reporting pavement data, to assist the decision makers in finding optimum strategies for maintaining pavements in serviceable condition over a given period of time for the least cost. A Pavement Management System (PMS) is designed to provide objective information and useful data for analysis so that road managers can make more consistent, cost-effective, and defensible decisions related to the preservation of a pavement network.

Pavement management must be capable of being used in whole or in part by various technical and administrative levels of management in making decisions regarding both individual projects and an entire highway network. A PMS is a set of tools to assist highway engineers and administrators in reaching engineering and budgetary decisions that will derive the maximum economic benefits from the funds available and enable the managing authorities to rationally justify adequate levels of funding to preserve and improve the highway network. The basic purpose of a Pavement Maintenance Management System is to answer the following:

a) Which maintenance and rehabilitation (M&R) measures should be carried out, when and where, given a certain management

b) The consequences of different funding level strategies by answering "what if" type of questions in terms of budget level or treatment choice.

1.2.1 Highway Development Management Software (HDM-4)

The Highway Development and Management (HDM-4) software tool, originally developed by the World Bank, 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. When considering the applications of HDM-4, it is necessary to look at the highway management process in terms of the following functions:

a) Planning
b) Programming
c) Preparation
d) Operations

Planning: It involves the analysis of the road system as a whole, typically requiring the preparation of medium to long term, or strategic, estimates of expenditure for road development and preservation under various budget and economic scenarios. Predictions may be made of road network conditions under a variety of funding levels in terms of key indicators together with forecasts of required expenditure under defined budget heads. The physical highway system is usually characterized at the planning stage by:

a) Characteristics of the road network Grouped in various categories and defined by parameters such as: road class or hierarchy, traffic flow/loading/congestion, pavement types , pavement condition.
b) Length of road in each category.

c) Characteristics of the vehicle fleet which use the road network .

The results of the planning exercise are of most interest to senior policy makers in the roads sector, both political and professional. A planning unit will often undertake this work.

Programming: Programming involves the preparation, under budget constraints, of multi-year road work and expenditure programmes in which sections of the network likely to require maintenance, improvement or new construction, are selected and analysed. It is a tactical planning exercise. Ideally, cost-benefit analysis should be undertaken to determine the economic feasibility of each set of works. The physical road network is considered at the programming stage on a link-by-link basis, with each link characterized by homogeneous pavement sections defined in terms of physical attributes. The programming activity produces estimates of expenditure in each year, under defined budget heads, for different types of roadwork and for each road section. Budgets are typically constrained, and a key aspect of programming is to prioritise the road works in order to find the best use of the constrained budget. Typical applications are the preparation of a budget for an annual or a rolling multi-year work programme for a road network, or sub-network. Managerial-level professionals within a road organisation normally undertake programming activities, perhaps within a planning or a maintenance department.

Preparation: Preparation is the short-term planning stage where road schemes are packaged for implementation. At this stage, designs are refined and prepared in more detail; bills of quantities and detailed costing are made, together with work instructions and contracts. Detailed specifications and costing are likely to be drawn up, and detailed cost-benefit analysis may be carried out to confirm the feasibility of the final scheme. Works on adjacent road sections may be combined into packages of a size that is cost-effective for execution. Typical preparation activities are the detailed design of:

a) An overlay scheme

b) Road improvement works

Preparation activities are normally undertaken by middle to junior professional staff and technicians within a design or implementation department of a road organisation, and by contracts and procurement staff.

Operations: Operations cover the on-going operation of an organisation. Decisions about the management of operations are made typically on a daily or weekly basis, including the scheduling of work to be carried out, monitoring in terms of labour, equipment and materials, the recording of work completed, and use of this information for monitoring and control. Activities are normally focused on individual sections or sub-sections of a road, with measurements often being made at a relatively detailed level. Operations are normally managed by sub-professional staff, including works supervisors, technicians, clerks and others. As the management process moves from Planning through to operations, it will be seen that changes occur to the data required.

1.2.2 HDM-4 without Calibrating Distress Models

HDM-4 is designed to make comparative cost estimates and economic evaluations of 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, discounting the future costs 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. The user defines a series of alternatives that describe different investment and preservation options for the road. The investments influence the condition of pavement over time and road maintenance costs. The pavement and traffic conditions have an influence on Road User Effects (RUE). The model predicts traffic speeds and the consumption of the RUE components, such as fuel, tyres etc. Multiplying these by the unit costs of the individual components gives the RUE over time. Comparing the cost outputs from various investment alternatives allows assessment of the relative merits, cost savings and benefits of the different alternatives using economic principles (Figure 1.1).

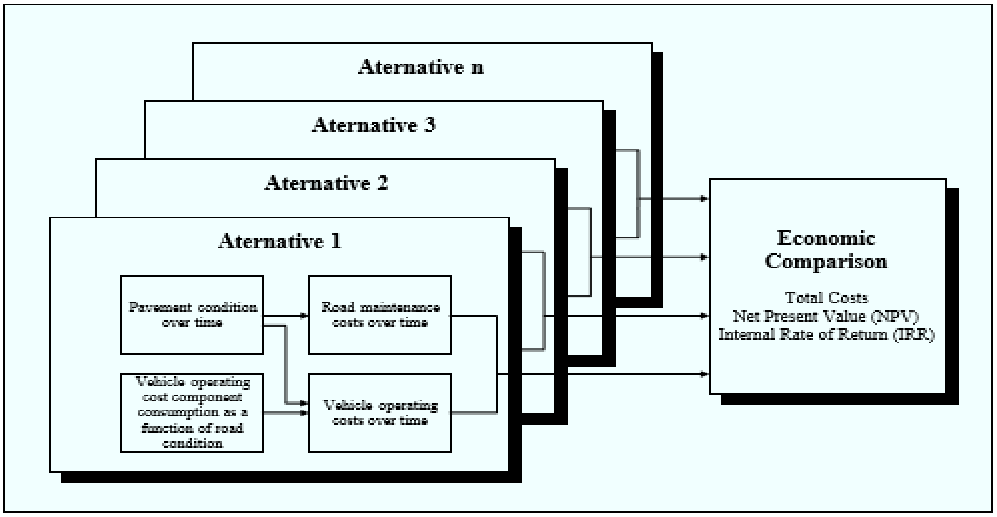


Figure 1.1: Steps of HDM-4 Approach

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.

This thesis presents necessary steps for the quality analysis using HDM-4 applications through control of data quality and calibration of the HDM-4 model. It describes the range of options for data collection and input to HDM-4, as well as accuracy considerations. The sensitivity of HDM to the input data is used to establish those data items that are most critical in the analysis. Similarly, the report discusses how one calibrates HDM-4 through its various calibration factors and the sensitivity of the model to these factors.

1.2.3 Need of Calibration of Distress Models

As part of the International Study of Highway Development and Management Tools (ISOHDM), a compendium was compiled of the countries where HDM had been applied. HDM or its relationships has been applied in over 100 developed and developing countries having markedly different technological, climatic and economic environments. Since the model simulates future changes to the road system from current conditions, the reliability of the results is dependent upon two primary considerations:

a) 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,

b) 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.

Application of the model thus involves two important steps:

a) 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.

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

c) The steps in modeling, from data to predictions to the model results are illustrated in Figure 1.2.

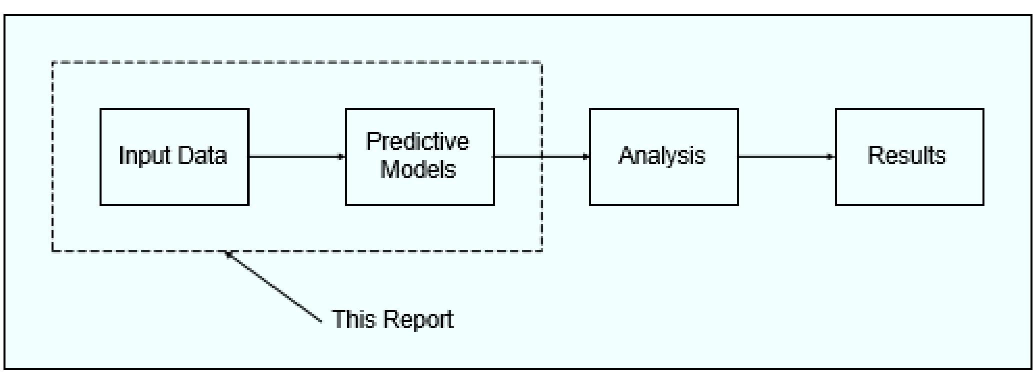


Figure 1.2: HDM-4 Modeling Process

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:

a) Road User Effects (RUE) - comprised of vehicle operating costs (VOC), travel time, safety and emissions, and

b) 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.

1.3 Case Study used for Calibration

Greater Noida is one of the most fast developing area and is an important town in the National Capital Region (NCR). The town has substantially attracted all round development be it commercial, industrial and residential etc. since Govt. of India has decided to develop NCR to decongest the capital city of India (Delhi). The selected case study for Sensitivity Analysis of distress deterioration calibration factors in HDM-4 tool is from Shani Temple to J.P. Associate Office Associate Office, a three Lane Dual Up and Down Carriageway in Sector 128 Noida. Length of Carriageway on one side is 1.4 km and same on the other side. Figure 1.3 shows the map of the selected carriageway for the project.

The traffic varies on both sides. The carriageway has been constructed 7 years ago and overlay is provided 2 years ago. The selected Carriageway is without shoulder.

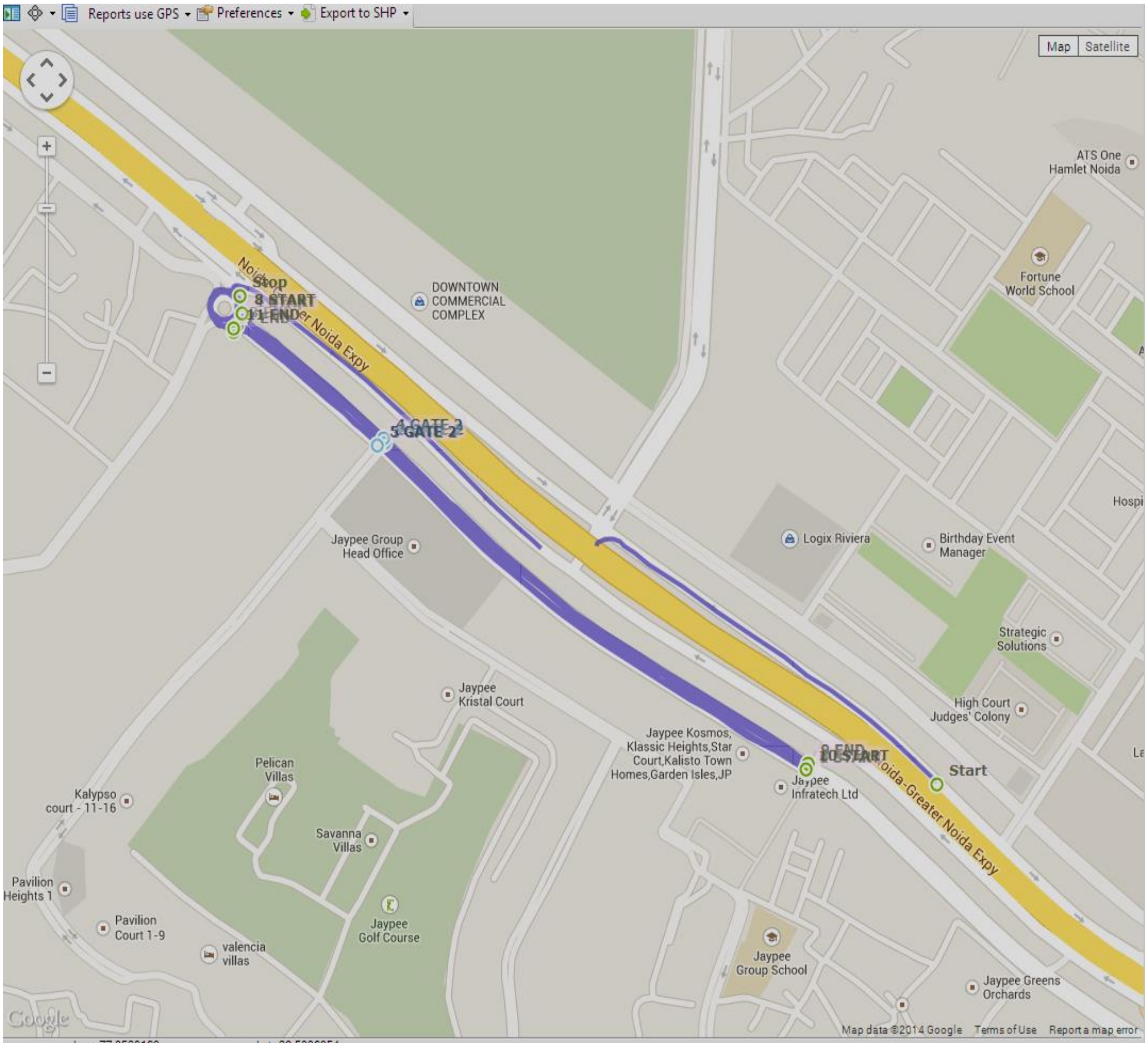


Figure 1.3: Map of the Carriageway Selected

CHAPTER 2

REVIEW OF LITERATURE

2.1 General

There is an immediate need for the development of scientific and economic based optimal maintenance policy for preservation of the huge network of roads recently being constructed in India. This scientific based approach will help in optimal utilizing the less maintenance budget provision for maintenance of roads and to preserve the huge assets of roads constructed. There is an immediate need to suggest economic analysis based optimum maintenance strategies for roads constructed and for different geographical conditions, and local traffic composition of India.

2.2 Studies of Pavement Management System

Kilareski and Churilla. (1983) recognized the importance of conserving resources and the need to maximize the purchasing power of limited budgets, related this to the state-of-the-art of pavement management. The special study methodology used for this research encompassed a literature search conducted to collect all pertinent information regarding Pavement Management Systems. The second task consisted of field visits to seven department engineering districts and various organizations in the central office. Interviews with management and engineering personnel at the district offices provided a look at how pavements were evaluated and programmed for improvements. The most obvious feature of the PMS, observed in other states, was the knowledge and decision making ability gained over an entire highway system. All of the states with a working PMS were able to produce a list of projects, ranked in a priority order, based upon an objective set of criteria. The criteria included some form of distress survey and an evaluation of roughness (ride). Some of the states used the PMS to predict the future condition of their pavement system. Predictions were based upon past performance and they are usually made for up to 20 years in the future. The capacity of predicting future performance allowed for the optimization of repair strategies and estimating future budgets. This lets management weigh the consequences of their decisions in terms of dollars spent and the overall condition of the pavements.

Rada et al. (1992) explained in their research work for the Integrated Airport Pavement Management System (IAPMS) believes that data base is the repository of all pavement information for the airfield network. The contents of the data base were organized in a hierarchical order on three separate levels I, II & III. A Functional Condition Module used in the functional evaluation of pavements consisted of analysis of sample unit, visual survey data, analysis and forecasting of section level visual survey data and prediction of time to functional failure. A Structural Condition Module was also used along with the traffic mix analysis module in the structural evaluation of pavements like analysis and forecast of load carrying capacity, structural remaining life, structural condition factor, and time to structural failure. The traffic mix analysis module was used to determine the loading history for the pavement. The maintenance and rehabilitation analysis module is used to select appropriate M&R activities, given a set of pavement conditions and intervention levels .The net effect was the preservation of investment in airfield pavement infrastructure through improved pavement performance and reduced maintenance and rehabilitation cost.

2.3 Pavement Performance Studies

Edward et al. (1995) derived Pavement roughness prediction models are generally simplifications of the actual relationships because of the complexity associated with the interaction between the various factors that affect deterioration. Models for roughness progression for flexible pavements using simplified incremental algorithms with actual field data of primarily variables are presented. The field data used is obtained for flexible pavements with lateritic gravel bases and sub bases with surface treatment as wearing course in Ghana, West Africa. The data covered major primary and secondary highways carrying a wide spectrum of traffic loading. The results indicate that environmental factors and structural capacity have significant influence on roughness progression. The strength of the pavement has a greater influence than the traffic loading on roughness progression, other factors remaining the same. Restoring the structural capacity of flexible pavements through timely maintenance intervention may help arrest the rate of deterioration. Direct transferability of models between different environmental, physical and operating conditions has its limitations and is not advisable.

2.4 Studies conducted at CRRI

Shah et al. (1997) represents that the concept of "serviceability" of roads and its evolution through time is widely accepted by pavement engineers and professionals as a way to evaluate road quality and conditions. Both the Present Serviceability Index (PSI) and International Roughness Index (IRI) can be used as indicators of road riding quality and serviceability. The objective of the study was to develop realistic models for estimating PSI for asphalt pavement sections located in the urban city of Noida, near Delhi, the capital of India. The PSI model was developed as a function of the pavement age. An attempt was made to calibrate the American Association of State Highway & Transportation Officials (AASHTO) equation for PSI and determine the suitability of this equation in Indian pavement conditions for selected urban roads. The developed models were also validated. Based on the developed PSI model, the maintenance alternatives have been suggested for the urban road sections in the study area.

2.5 Studies conducted in China

Liu. (2006) developed Pavement management system in china. Over 1,900,000 km roads had been constructed in China, among them 40,000 km roads were expressways, another 15,000 expressways would have been constructed by 2010 (Liu 2006).By 2020, a national highway network would be completed with 85,000 expressways. Clearly, China needed a pavement management plan to address past and future pavements. In 1984, China initialized and developed a PMS and since its introduction significant progress, in terms of pavement management, has been made. The implementation of this PMS has not gone so well, due to less focus and acceptance. Most transportation departments in China are more focused on road construction.

2.6 Road User Cost Studies

Daba et al. (2006) carried out a study to highlight the present pavement maintenance practice around the world with a particular attention to the maintenance trend in India and use Highway Development and Management (HDM-4) for the maintenance of a test section in Mumbai Metropolitan Region (MMR). This region has a humid, warm, and wet climate prevalent in the west coast of India. The test section has seven layers and is a six lane divided highway. Condition responsive maintenance has been only cracking and roughness has been found out to be critical out of eight deterioration models in HDM-4 for the analysis period of 15 years. The condition of the pavement has become equivalent to new one after maintenance.

Aggarwal et al. (2010) studied on strategies on highlighting some basic issues for sustainable maintenance of rural roads. This study also identifies some strategies for rational uses of limited resources available for maintenance, strategies to provide required level of funding, strategies to strengthen the institutional measures and strategies for developing data base for sustainable maintenance of rural road network in India. A basic framework has also been presented that can be used for developing a maintenance management system for rural roads in India.

Jain et al. (2013) considered the study which consisted of one Expressway and National Highway. Expressway had been divided into five subsections and NH had been divided into8 sub-sections. The sub-sections so divided were quite homogeneous within themselves as far as climatic and geometric conditions are considered but vary considerably from each other in traffic characteristics and pavement surface conditions. Input data for the study was defined as the 'Multilane Highway Network' and 'Multilane Vehicle Fleet' database files which included various parameters. The total traffic in terms of Annual Average Daily Traffic (AADT), initial composition of various vehicles for the selected pavement sections had been used for the analysis in HDM-4. Functional evaluation was based on collection of road data pertinent to surface distress like crack area, pothole area with depth, raveled area, rut depth, surface roughness. The type and extent of distress developed at the surface were observed, based on visual condition survey. The first alternative was the basic routine maintenance for crack, pothole and ravel patching. It was considered as the Base Alternative/Routine Maintenance for the analysis. Other alternatives included Resealing with 25 mm Semi Dense Bituminous Concrete (SDBC). Overlay of 40 mm Bituminous Concrete (BC), Resealing with overlay of 40 mm BC over that 25 mm SDBC and the last alternative was strengthening with overlay of BC 40 mm upon Dense Bituminous Macadam (DBM) of 50 mm thickness. The intervention criteria's for various alternatives were selected accordingly. One of main objectives for long-term pavement management was to find the optimal number of maintenance treatments and the best timings and intensities thereof to maintain a given road section during a predefined analysis period *T*. Overall objective of this research work was to tackle the lack of innovative techniques and to support decision-making on optimal strategies of investment and preservation for road infrastructure. HDM-4 has emerged as a very powerful tool for developing various aspects of pavement maintenance management system such as predicting the pavement deterioration, programming of maintenance and rehabilitation works, carrying out lifecycle cost analysis and cost optimization.

2.7 Calibration Studies

Dattatrayas et al. (2013) carried out a study that Highway Development and a Management System (HDM-4) developed by World Bank is a powerful pavement management software tool capable of performing technical and economic appraisals of road projects, investing road investment programs and analyzing road network preservation strategies. Its effectiveness is dependent on the proper calibration of its predictive models to local conditions. The use of appropriate calibration factors in HDM-4 pavement deterioration models will facilitate more reliable and rational prediction of pavement deterioration for the road network under considerations. This in turn will help in better assessment of the maintenance and rehabilitation requirements of pavements and improved pavement management system. In the present study, computer programs in 'Visual C' language have been developed for calibration of pavement deterioration progression models stipulated in HDM-4 tool such as cracking, raveling, edge break and pothole for surface treatments with unbound base types of pavement composition used for Low Volume Roads (LVR) in India.

Chandrama et al. (2013) explained that HDM-4 tool has been widely used for the pavement management activities across the world. This tool has inbuilt pavement performance prediction models, vehicular performance models and economic analysis tools. Exhaust emissions are one of the important outputs of vehicular performance models that are helpful in assessing viability of investment options and environment impact assessment activities. There are seven exhaust emission models (for different components like hydro carbon, carbon monoxide, particulate emissions etc.) available within HDM-4. These models are required to be calibrated so that the predictions made by calibrated HDM-4 models represent the specific local ground conditions. The work presented here is an attempt to calibrate the HDM-4 emission models to Indian conditions. Initially sensitivity analysis of emission models was conducted to find sensitive input variables in emission model that affect model output significantly. It was found that operating weight, pavement gradient and vehicle life are very sensitive inputs into HDM-4 emission models. Based on the sensitivity analysis and data obtained from a previous study were used in calibration of emission models for Indian conditions. Further these calibrated emission models were used to predict emissions for urban conditions prevailing in India. Comparison of predicted and measured values indicate that all emission models for two lane road and Carbon Monoxide emission model for four lane road over-predicts for two wheelers, car, light commercial vehicles and busses, while under-predicting for trucks.

CHAPTER 3

FIELD DATA COLLECTION OF THE STUDY

3.1 General

A variety of activities / tasks were carried out under the field investigations with a view to assess the structural and functional condition of existing pavement, so that the suitable recommendations on corrective measures for its improvement can be suggested. The following studies, in the field, were undertaken:

- Assessment of pavement surface condition
- Roughness measurements
- Benkelman Beam deflection measurements
- Traffic volume studies
- Test pit observations

The detailed methodology adopted for carrying out the above activities in the field and the data / results obtained therefrom are presented in the following sub-sections.

3.2 Assessment of Pavement Surface Condition

Data on pavement surface condition collected for a road provides a preliminary insight about the pavement's construction quality and its likely performance on long term basis. It also assists in making an assessment about the user's comfort in terms of safety as well as in establishing Maintenance and Rehabilitation (M&R) priorities / strategies. The basic measurements in evaluating the pavement surface condition are to determine the level of existing surface distress, based on the visual inspection of pavement surface. Uses of such data are primarily based on the engineering experience and judgment.

Surface condition data is used as one of the indicators to identify structural and functional deficiencies. Based on this data and other information, the causes of pavement surface distress, maintenance treatments needed and selection of appropriate corrective measures are generally decided and applied.

The various types of major surface distress, recorded for the project road, in terms of percentage of total pavement's surface area (on per kilometer basis) were cracking, raveling, pot holes, shoving, bleeding, corrugations and rutting / settlement / undulations.

Pavement surface condition surveys are generally conducted by any one of the following two methods:

(i) Walk survey- associated with or without actual measurement

(ii) Drive survey

In a walk survey, a team of experienced highway engineers walks along the road, inspects the road condition and makes visual observations on the types of distress developed and their extent/magnitude. The actual measurements may also be carried out on a representative and relatively shorter stretch.

In a drive survey, the team travels along the road in a vehicle at a slow speed (say 10 to 20 km/hr) and records the surface condition by visual observations. The data is recorded at convenient interval (unit lengths of the stretch), say a kilometre, by noting down the distress in each kilometre.

In view of the time constraints, visual condition survey for the project road was conducted mainly by driving in a vehicle at a slow speed of say, about 10 to 20 km/hour and later on finalized by walk survey also. The assessment of pavement surface condition, in both directions of travel (i.e. from Shani Temple to J.P Associates Office and from J.P Associate Office to Shani Temple), on the study section, was done by a team of two experienced scientists from CRRI, partly by walking and, as and when required, by driving at a creep speed. The different types of distress, as observed on the pavement surface, were recorded as affected area in terms of percentage of total surface area. The types of distress and their extent, as observed on kilometer wise basis, in Up and Down directions of the project road was found to be almost same and are given in Table 3.1.The typical surface condition in terms of surface defects observed at a few selected locations, in both carriageways, is illustrated in Plates 3.1 to 3.4.

Plate 3.1: View of Slippage on Shani Temple to J.P.Associate Office

Plate 3.2: View of Raveling on Shani Temple to J.P. Associate Offic

Plate 3.3: View of Pothole and Ravelling on J.P. Associate Office to Shani Temple

Plate 3.4: View of Patching and Ravelling on J.P. Associate Office to Shani Temple

Table 3.1: Visual Stress Measurement

Carriageway Width (m):			
Chainage of Test Section:	LHS	Date of Observation:	30.04.14
Type of Surface:	Flexible	Weather Condition:	

Chainage (km)		Cracks		Patch Work	Potholes	Shoving	Rut Depth	Drainage & Shoulder condition
From	To	Type of Crack	(%)	(%)	(%)	(%)	(mm)	
1.21 2.61	2.61 1.21	Aligator	10 – 15	10 - 15	0-1	0-1	0 - 5	Good
Total to be found the same in both directions		Aligator	10 – 15	10 - 15	0-1	0-1	0 - 5	Good

3.3 Roughness Measurements

There are simple as well as sophisticated equipment, available worldwide, for measurements of both longitudinal and transverse profiles which differ from country to country. The measurements of road roughness, under this project, were taken up by Laser based Profilometer, popularly known as Automated Road Survey System / Network Survey Vehicle.

Laser based road profiling is a high speed road roughness measuring system. The Laser Profilometer beam is installed in front of the survey vehicle. The field measurements using Laser Profilometers can be done at speeds ranging from 30 to 100 kmph. This system is based on the measurement of vertical displacements using Laser Rays. Laser Profilometer Bar comprises of two Laser sensors used for measurement of longitudinal profile of the pavement surface. These sensors are placed along the wheel path of survey vehicle. The system directly gives International Roughness Index (IRI) for both wheel paths viz. Left IRI and Right IRI in terms of m/km.Plate-5 shows the Automated Road Survey System being used on the Project Road for measurement of Pavement Surface Roughness.

Plate3.5: Automated Road Survey System Being Used on the Project Road for Measurement of Pavement Surface Roughness

Presentation of Roughness Data

It is a well-accepted fact that road users are primarily concerned with the riding quality/comfort, a road provides. A term called "Present Serviceability Rating (PSR)" is used extensively to classify the riding quality being offered to the road users which is directly related to its current surface condition and to the roughness level. PSR is also applied to make a subjective judgment about the ability of a pavement surface in terms of the service it provides to the users.

Roughness data collected, under this assignment by using Network Survey Vehicle, on dual 3 lane carriageway (km 0 to km 1.400) for Up & Down carriageways and data has been assumed for the intermediate lane.

Lane wise data on International Roughness Index (IRI) in m/km and Roughness Index (RI) converted into mm/km, by applying World Bank's Equation as given below, along with average, maximum and minimum values of IRI and RI are presented in Table 3.2 and Table 3.3.

RI = 630 (IRI) ^1.12

Where, IRI is in m/km and RI is in mm/km

[World Bank's Equation for Conversion of IRI into RI]

Table 3.2: Roughness Index for Up Carriageway (Shani Temple To J.P. Associate Office)

(Km 0 to Km 1.40)

Chainage (km)		**Inner Lane**		**Outer Lane**	
From	**To**	**International Roughness Index (m/km)**	**Roughness Index (mm/km)***	**International Roughness Index (m/km)**	**Roughness Index (mm/km)***
0.000	0.250	2.1	1446.2	2.6	1837
0.250	0.500	2.5	1758	2.4	1679.5
0.500	0.750	2.4	1679.5	2.3	1601.3
0.750	1.000	1.9	1292.8	1.8	1216.9
1.000	1.400	2	1369.2	2.1	1446.2
Average of the Lane		**2.18**	**1508**	**2.24**	**1554.5**
Maximum Value		**2.5**	**1758**	**2.6**	**1837**
Minimum Value		**1.9**	**1292.8**	**1.8**	**1216.9**

Table 3.3: Roughness Index for Down Carriageway (J.P. Associate Office To Shani Temple)

(Km 1.400 to km 0)

Chainage (km)		**Inner Lane**		**Outer Lane**	
From	**To**	**International Roughness Index (m/km)**	**Roughness Index (mm/km)***	**International Roughness Index (m/km)**	**Roughness Index (mm/km)***
1.400	1.000	2.4	1679.48	2.5	1758
1.000	0.750	2.6	1837	2.3	1601.3
0.750	0.500	2.1	1446.2	1.8	1216.9
0.500	0.250	1.8	1216.9	2.2	1523.5
0.250	0.00	2.2	1523.5	2.1	1446.2
Average of the Lane		**2.22**	**1539**	**2.18**	**1508**
Maximum Value		**2.6**	**1837**	**2.5**	**1758**
Minimum Value		**1.8**	**1216.9**	**1.8**	**1216.9**

3.4 Benkelman Beam Deflection Measurements

To determine the present structural adequacy of the project road, non-destructive method of Benkelman Beam rebound deflection has been used. A standard two-axle truck, having rear axle load of 8.16 tonnes and tyre pressure of 5.6 kg / cm^2 was used for measuring the deflections. The deflection measurements were taken according to IRC: 81-1997. The pavement temperatures were measured at regular intervals by a standard thermometer for applying the needed temperature correction factor, when the pavement temperature differs from the standard pavement temperature of 35^oC. For applying the correction factor for subgrade moisture content, samples of subgrade soil were collected from the test pits dug upon the subgrade level which were oven dried in the laboratory for finding out the subgrade moisture content.

Necessary corrections for temperature and subgrade moisture were applied to the observed rebound deflections, as per IRC: 81-1997, and characteristic deflections calculated, separately for each kilometre long section as well as for the entire carriageway. Table 3.4 presents characteristic deflection (Dc) values computed lane wise, for each kilometre section in both carriageways. Calculation of the deflection data for both sides of the carriageway is shown in Annexure 2 and Annexure 3 respectively. Table 3.4 shows the characteristics deflection values on both the sections of the project road

Table 3.4: Deflection Measurement Data

S.No	**Name of the section**	**Characteristics Deflection, D_c**
1.	Shani Temple to J.P. Associate Office	1.86
2.	Shani Temple to J.P. Associate Office	1.83

Plate 3.6: View of Startup of Benkelman Deflection Beam Testing

Plate 3.7: View of Benkelman Deflection Beam

3.5 Traffic Volume Survey

Traffic volume survey was conducted for a continuous period of 24 hours (i.e. from 9.00 PM of 2nd May, 2014 to 9.00 PM of 3rd May, 2014) by engaging skilled enumerators, separately for up and down directions, covering all categories of vehicles including non-motorized traffic. The carriageway consists of pedal cycles, cycle rickshaw, hand/animal drawn vehicle, Scooters, cars/jeeps, three wheeler, pick up vans, light commercial vehicles, light passenger vehicles, two axle truck, multi axle truck, buses, and tractor trolley. Calculation of the traffic count for both sides of the carriageway is shown in Annexure 1 and Annexure 2 respectively. The total traffic volumes (24 hours) of different categories, for both up and down directions, are given in Table 3.5 and Table 3.6.

Table 3.5: Total Traffic Volume from Shani Temple to J.P. Associate Office

S.No	Time Span	Motorized vehicle	Non-Motorized Vehicle	Total vehicle	% composition
1	7am-12pm	1290	51	1341	36.23
2	12pm-4pm	925	37	962	25.99
3	4pm-9pm	1127	96	1223	33.05
4	9pm-7am	171	4	175	4.73

Table 3.6: Total Traffic Volume from J.P. Associate Office to Shani Temple

S.No	Time Span	Motorized vehicle	Non-Motorized Vehicle	Total vehicle	% composition
1	7am-12pm	39	889	928	30.9
2	12pm-4pm	30	824	854	28.4
3	4pm-9pm	44	820	864	28.7
4	9pm-7am	9	353	362	12

3.6 Test Pit Observation

Based upon the visual condition survey (surface distress data), the locations of test pits were decided and were located on wheel paths. A total of three test pits, two in the Up direction (Shani Temple to J.P. Associate Office) and one in the Down direction (J.P.Associate Office to Shani Temple), measuring 1.2 m x 1.2 m in size, were dug open upto the subgrade level, at selected representative locations. The locations and details of test pits are given in Table 3.8. The thickness of each constituent layers was measured at each of the test pits and average value was taken. The conditions of surface and surroundings, near the locations of each test pits were also noted. The samples of bituminous materials (mixes), granular materials, and the subgrade soils, from each test pits, were also collected from the test pits for detailed evaluation in CRRI laboratory.

Table 3.7: Thickness and Density of Cores

Core No.	Thickness of BC (mm)	Thickness of DBM (mm)	Total Bt.
1	25 (broken)	50	75
2	40	40	80
3	48	55	103
4	30	65	95
5	30	70	100
6	50	50	100
7	25 (broken)	48	73

Plate3.8: View of Test Pit Testing

Plate3.9: View of Instrument of Test Pit Testing

CHAPTER 4

SELECTION OF BEST MAINTAINANCE STRATEGY WITH HDM-4

4.1 General

Presently, number of tools or mechanisms are available that allow them to make a better use of the available resources for the Maintenance and Rehabilitation (M&R) of pavements but are not globally acceptable and lack in implementation. The World Bank's HDM-4 is internationally recognized tool for making timely and cost effective maintenance management decisions for a road network. It can assist the road agencies for establishing realistic levels of funding, and to set levels and priorities to maximize the effectiveness of expenditure on pavement maintenance activities. Therefore, HDM-4 system has been selected and used in this study for achieving the objectives. This chapter presents the required inputs of various data in HDM-4.

4.2 General Information on Input Data

The input data comprises of category of road, its length, width, surface type, thickness of different layers, climate zone, construction history data which includes construction year and year of major/minor periodic/preventive treatments, existing road surface condition, surface material strength values, etc. It also contains road geometry data viz. horizontal curvatures and gradient (Rise/Fall) per km. Figure 4.1 presents pictorial representation of Annual Averagge Daily Traffic (AADT) which comes under module Road Network Aggregate Parameters. The values of other parameters under the module includes pavement strength, bituminous layers, surface distresses, surface texture, geometry of the carriageway, construction quality and roughness. All the above mentioned parameters can be changed as per the existing specifications/codes suiting to the local conditions.

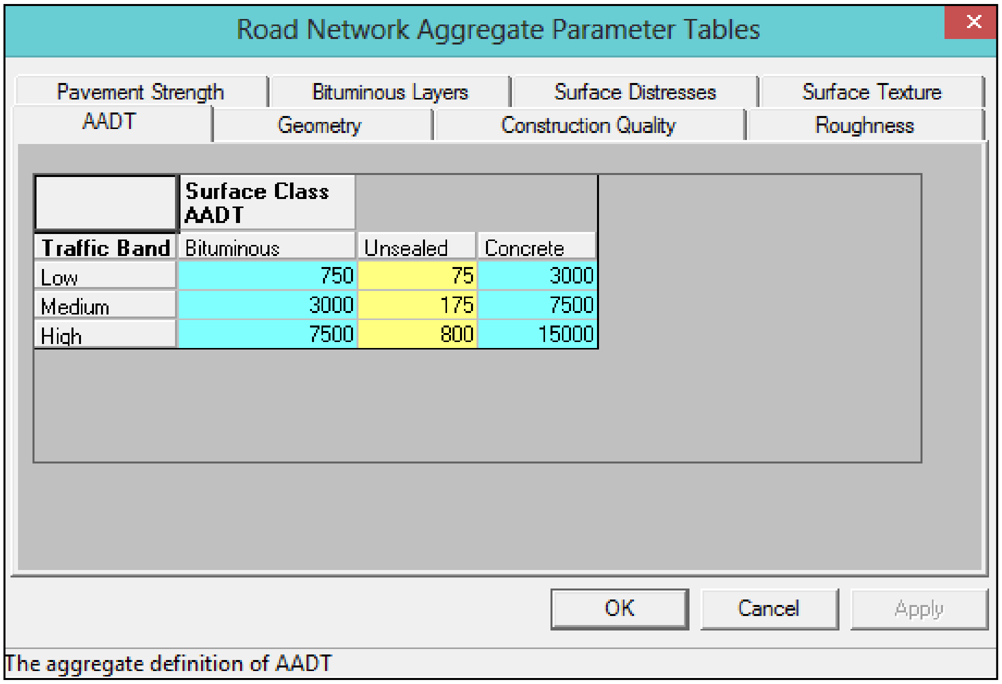


Figure 4.1: Defining Road Network Aggregate Parameter

4.2.1 Defining Currency

All the outputs are based on the given unit cost of any road activities in HDM-4 and are optimized based on economic analysis. Therefore local currency has to be defined while running the HDM-4 software. Figure 4.2 shows the Indian currency that is added in the software. In the software any currency of any country can be added/deleted and the corresponding symbol and symbol position can be noted.

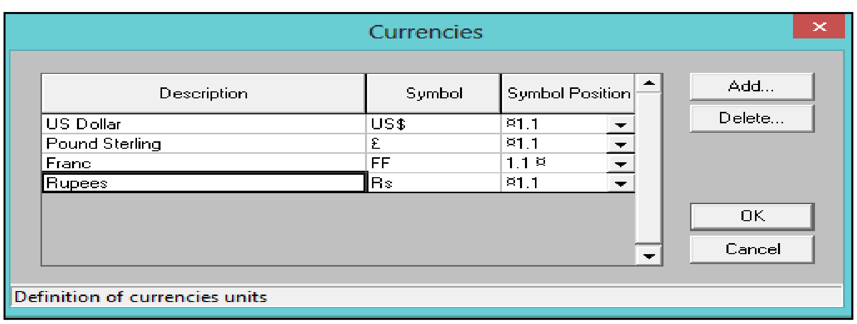


Figure 4.2:Defining Currency in Software

4.2.2 Defining Climate Zone

Figure 4.3 presents the pictorial view of climate input parameters which depends on the study area i.e. Noida, U.P. The moisture classification and temperature classification needs to be entered of the study area from the given options. Corresponding to it the given default moisture and temeperature classification, all related other values of the climate zone are entered automatically by default which can be changed if needed.

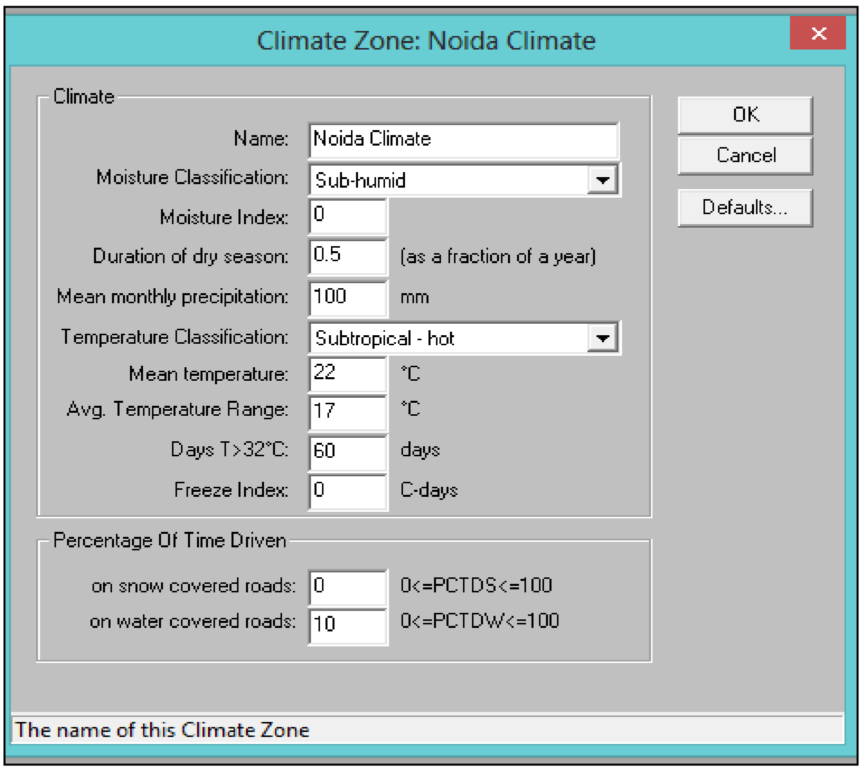


Figure 4.3: Input of Climate Zone

4.2.3 Defining Speed Flow Type

Speed flow type of any road network depends on the exisitng Anual Daily Traffic (ADT) which specifies the peak and off-peak hours. Accordingly for study road, speed flow type has been identified based on the traffic studies. The speed flow type of the study road has been presented in Figure 4.4. The related parameters with speed flow type based on single lane, dual lane, wide two lane road, intermediate lane road, etc. are given as default value and accordingly the default values of ultimate capacity, free flow capacity, nominal capacity and Jam Speed are entered automatically. If needed and beased on research these values can be changed. It also includes accident rates and and Speed related calibration data.

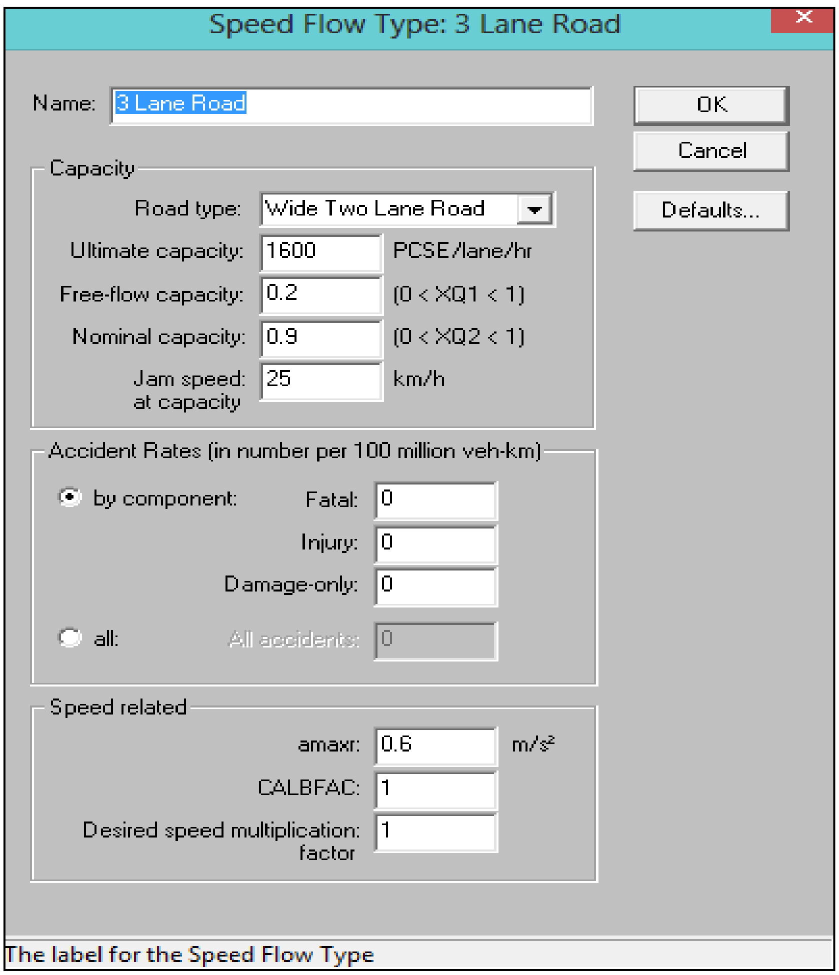


Figure 4.4: Speed Flow Type of the Study Area

4.2.4 Defining Traffic Flow Pattern

Figure 4.5 shows the existing traffic flow pattern of the stucy road which includes road use and flow distribution data . Flow distribution data for the presnt case has been divided into four different timing span based on the peak and off-peak traffic flow. There are namely two method defined in the software viz. Hourly Volume (HV) method and Percentage AADT (PCNADT) method. In the present study PCNADT method has been selected which includes hours per year of each flow period and percentage of traffic withing the four flow periods.

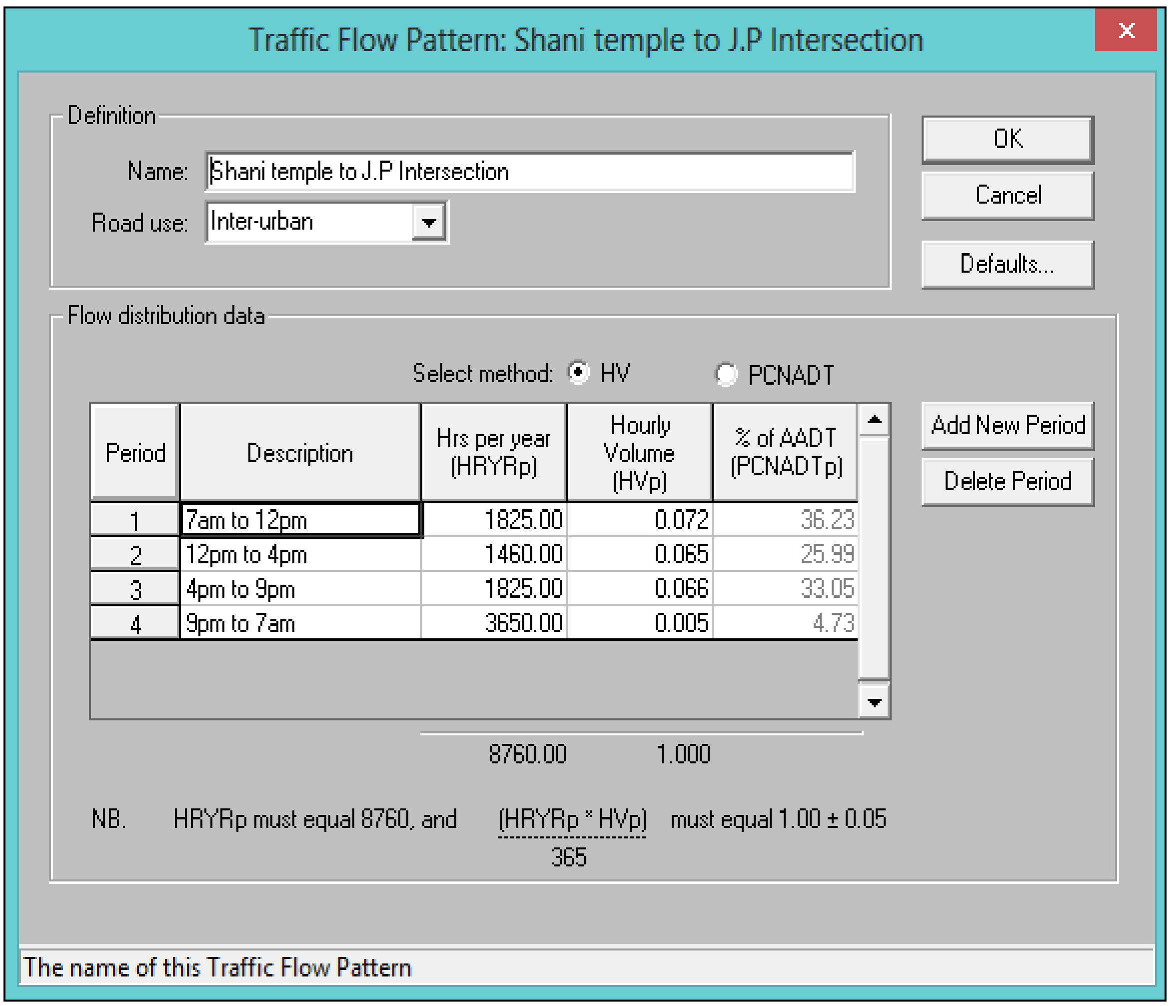
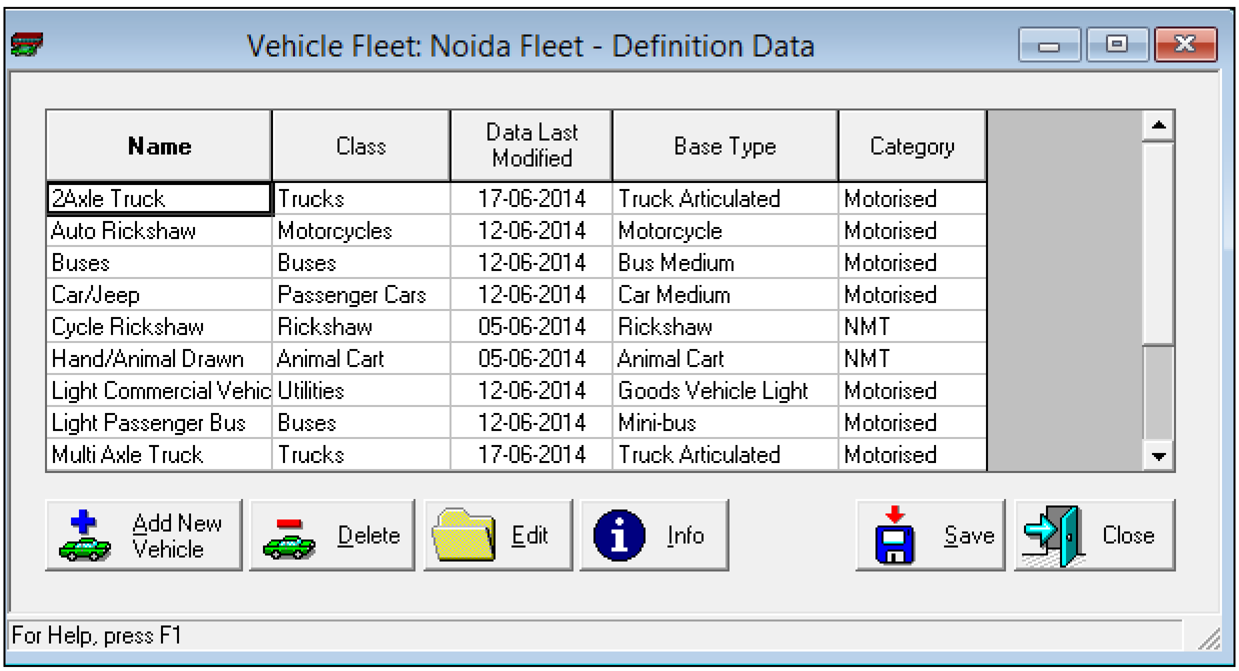


Figure 4.5: Traffic Flow Period

4.2.5 Defining Vehicle Fleet of the Study Road

The exisitng vehcile fleet plying on the study road has to be defined in the software. Each category of vehicle plying on the existing road has to be identified accordingly and their attributes and basic characteristics with cost are to be entered in the software. Figure 4.6 presents the actual category of vehicle plying on the road by defining it as vehicle fleet of Noida. The attributes and basic characteristics of all individual vehicles are given separetly by opening the page of individual vehicles. Basic characteristics of the vehicle includes passenger car space equivalent, number of wheels, number of axles, type of tyre, utilization of the vehicle and loading and operating weight of the vehicle.



Name	Class	Data Last Modified	Base Type	Category
2Axle Truck	Trucks	17-06-2014	Truck Articulated	Motorised
Auto Rickshaw	Motorcycles	12-06-2014	Motorcycle	Motorised
Buses	Buses	12-06-2014	Bus Medium	Motorised
Car/Jeep	Passenger Cars	12-06-2014	Car Medium	Motorised
Cycle Rickshaw	Rickshaw	05-06-2014	Rickshaw	NMT
Hand/Animal Drawn	Animal Cart	05-06-2014	Animal Cart	NMT
Light Commercial Vehic	Utilities	12-06-2014	Goods Vehicle Light	Motorised
Light Passenger Bus	Buses	12-06-2014	Mini-bus	Motorised
Multi Axle Truck	Trucks	17-06-2014	Truck Articulated	Motorised

Figure 4.6: Category of Vehicles under Noida Vehicle Fleet

4.2.6 Defining Road Network of the Study Road

HDM-4 analysis is based on the exsiting road network under study. All the variable related to road geometrics, terrain, drain conditions, existing crust thisckness with pavement strength in terms of deflection / structural number, historical pavement constrcution and preventive / periodic treatments, existing pavement condition are to be entered in HDM-4. The pictorial views of entered data are presented from Figure 4.7 to Figure 4.10.

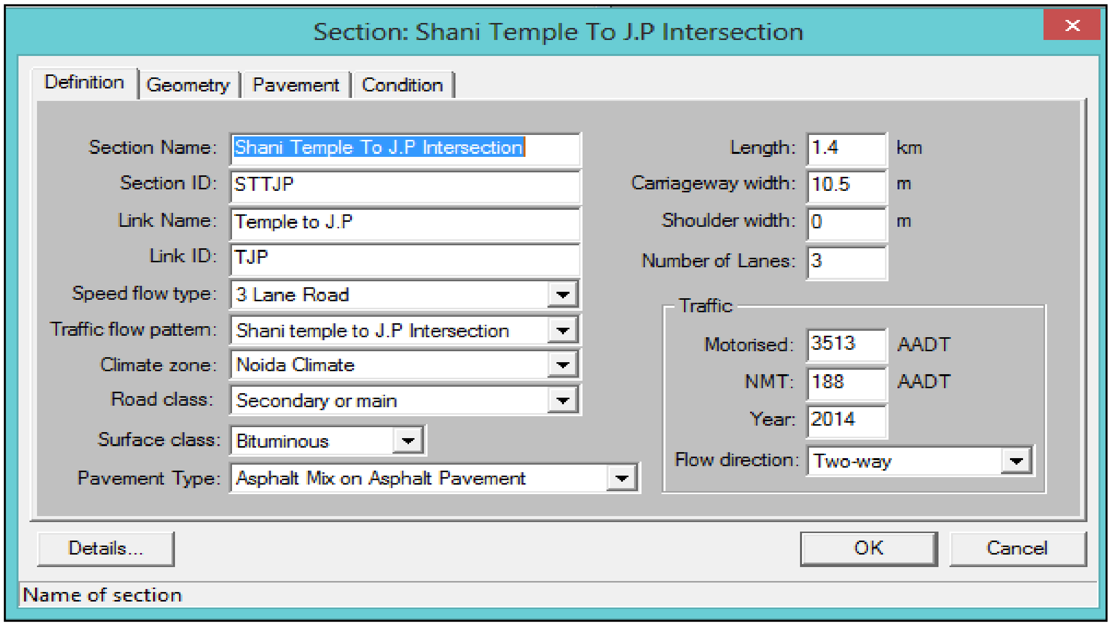


Figure 4.7: Study Of Road Network

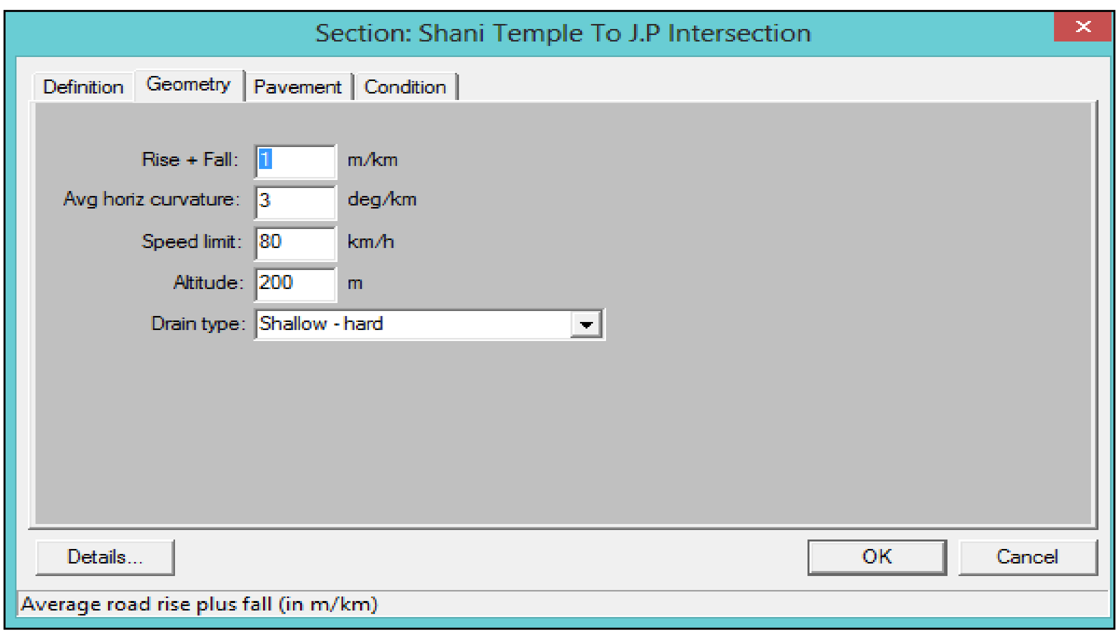


Figure 4.8: Road Geometry of the Study Road

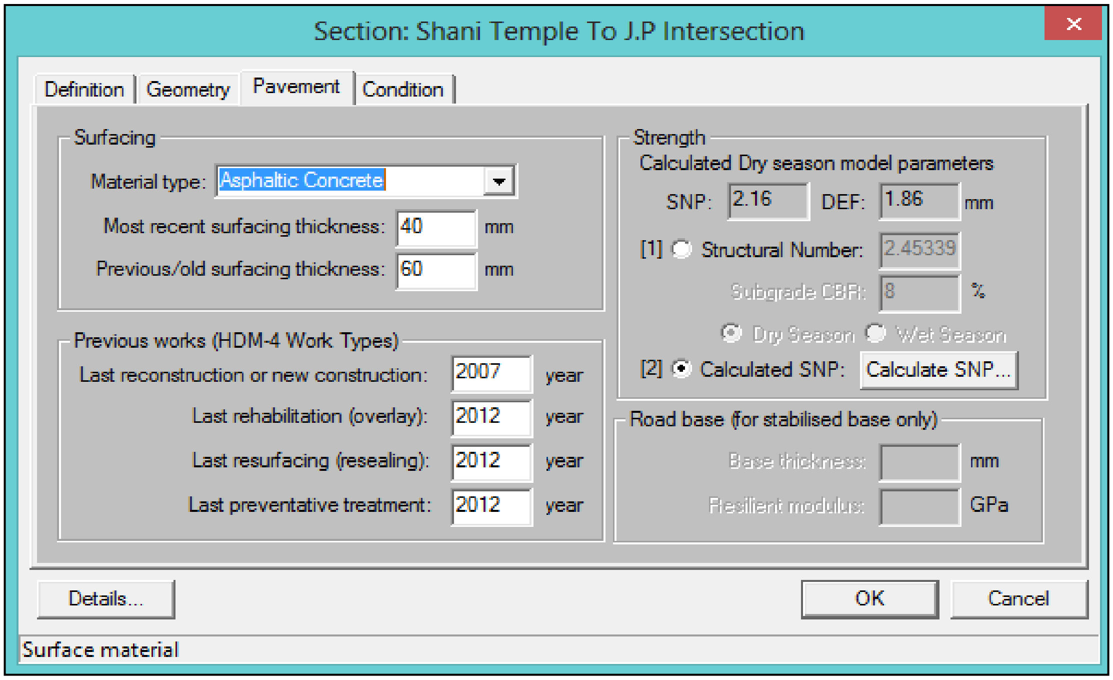


Figure 4.9: Road Characteristics

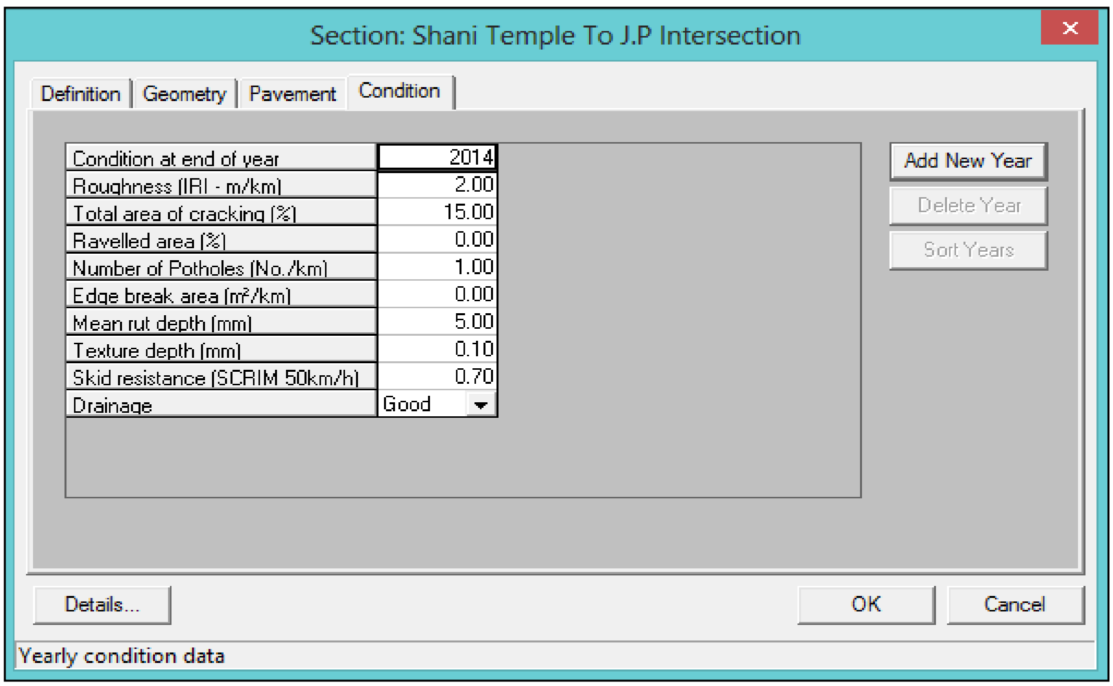


Figure 4.10: Existing Road Condition

This values presented in above given Figures are found through extensive field surveys which includes roughness syrvey, distress observations, benkelman beam survey, test pit observations, etc. which are already given in Chapter 3.

4.3 Maintenance and Rehabilitation Strategies

The maintenance and rehabilitation strategies defined in the present study are based on the prevalent maintenance strategies existing in Noida. It was finalized after having discussions with the various engineers involved in the project. The details are presented in Table 4.1. Looking into the objectives of the report the intervention criteria has been kept constant for each aletrnative so that the comparison of the alternative can be done.

Table 4.1: Proposed Maintenance Strategies and Intervention Criteria for Project Analysis

Maintenance Strategy	**Base Alternative**	**Alt 1**	**Alt 2**	**Alt 3**	**Alt 4**	**Alt 5**
Description of Work	Pothole Repair, Crack sealing	Surfacing by 25mm SDBC	ST 25mm SDBC+40mm BM	40mm BC	70mmDBM+40 mmBC	Microsurfacing
Intervention Level	Pothole >=4 For Pothole Repair Wide Structural Cracking>=5%	Total Carriagewa y Cracked>= 15%	Total Carriageway Cracked>=15 %	Total Carriageway Cracked>=15%	Total Carriageway Cracked>=15%	Total Carriageway Cracked>=15%

4.4 Basic Data Inputs for Project Analysis

Before executing the project analysis module built in HDM-4 software, it is essential to complete all necessary inputs required as minimum basic structure in the software. These include configuring the aggregate data, development of vehicle fleet, development of road network, development of maintenance alternatives, etc. After inserting the basic data inputs, the project analysis can be made to run by attaching the different basic modules. It is necessary to have an optimum maintenance alternative for life cycle analysis obtained through economic analysis. The HDM-4 project analysis has been carried for entire life cycle analysis of 20 years for the selected pavement section. All the identified alternatives were then compared with respect to base alternatives considered herein as maintenance alternative having minimum maintenance. . The pavement deterioration readings for all maintenance strategies as were generated for the analysis period of 20 years i.e. from 2015-2034.

4.4.1 Details of Data used in Project Analysis

All the alternative maintenance strategies have been applied on both of the existing study sections (up and down carriageway) for the analysis period of 20 years. The pavement deterioration data of the both sections (Shani Temple to J.P. Associate Office and J.P. Associate Office to Shani Temple) as observed in the field are already given during creation of road network.

4.4.1.1 Creation of Project in HDM-4

The pictorial view of the tabs related to analysis period, currency, road network, percentage of vehicles and growth and attachments of alternatives for creation of project have been given in Figure 4.11 and Figure 4.14. The analysis of study road sections is for 20 years life cycle analysis as given in Figure 4.11. In the same way, each sections are to be included separately and unique description with identification has to be assigned. The section details which includes section definition, section geometry, pavement and pavement condition can be found by double clicking on the section in the select section tab page.

Figure 4.13 displays only those vehicles that were identified (from J.P Associate Office To Shani Temple) for the study section in the analysis. This names of the catgory of vehicle defines the range of vehicle types that is found and assigned to the road section. The assignment of traffic by section is done by clicking the Define Normal Traffic Tab. Vehicle attributes for a particular vehicle type can be reviewed by double-clicking on the appropriate vehicle type descriptions. The vehicle attributes are under four tabs viz. definition, basic characteristics, economic unit costs and financial unit costs.

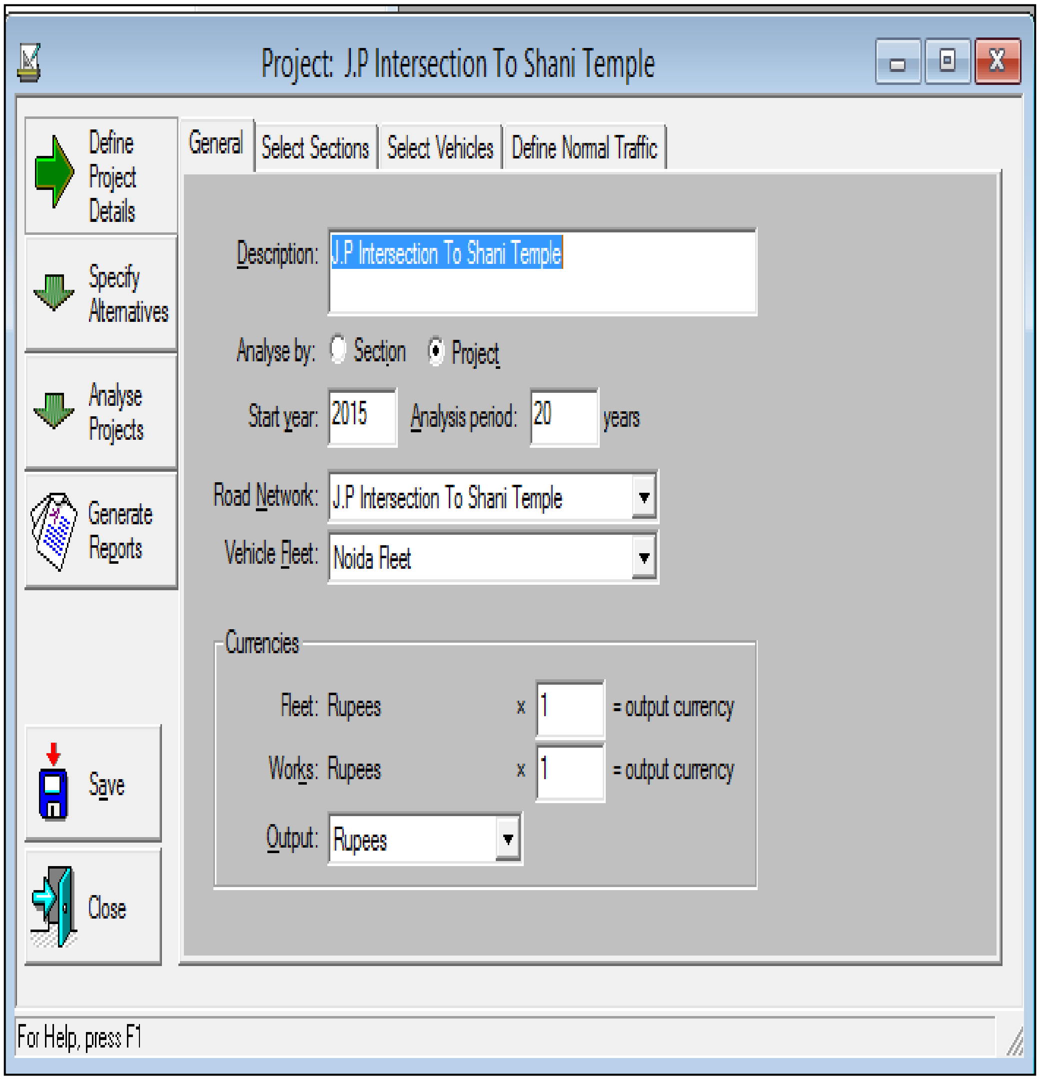


Figure 4.11: Defining Analysis Period and First Tab of Project in the Software

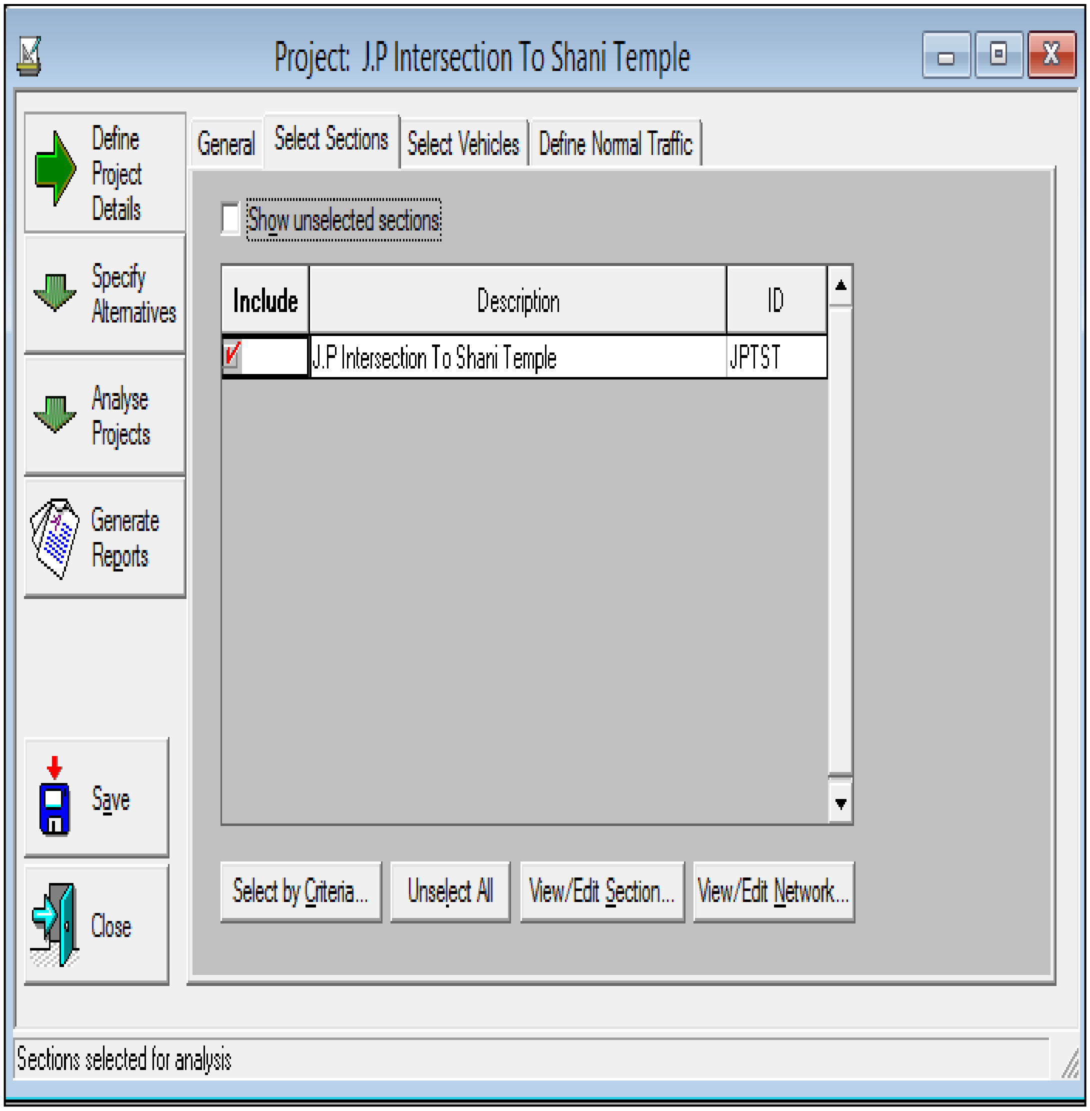


Figure 4.12: A View of Study Section Inclusion

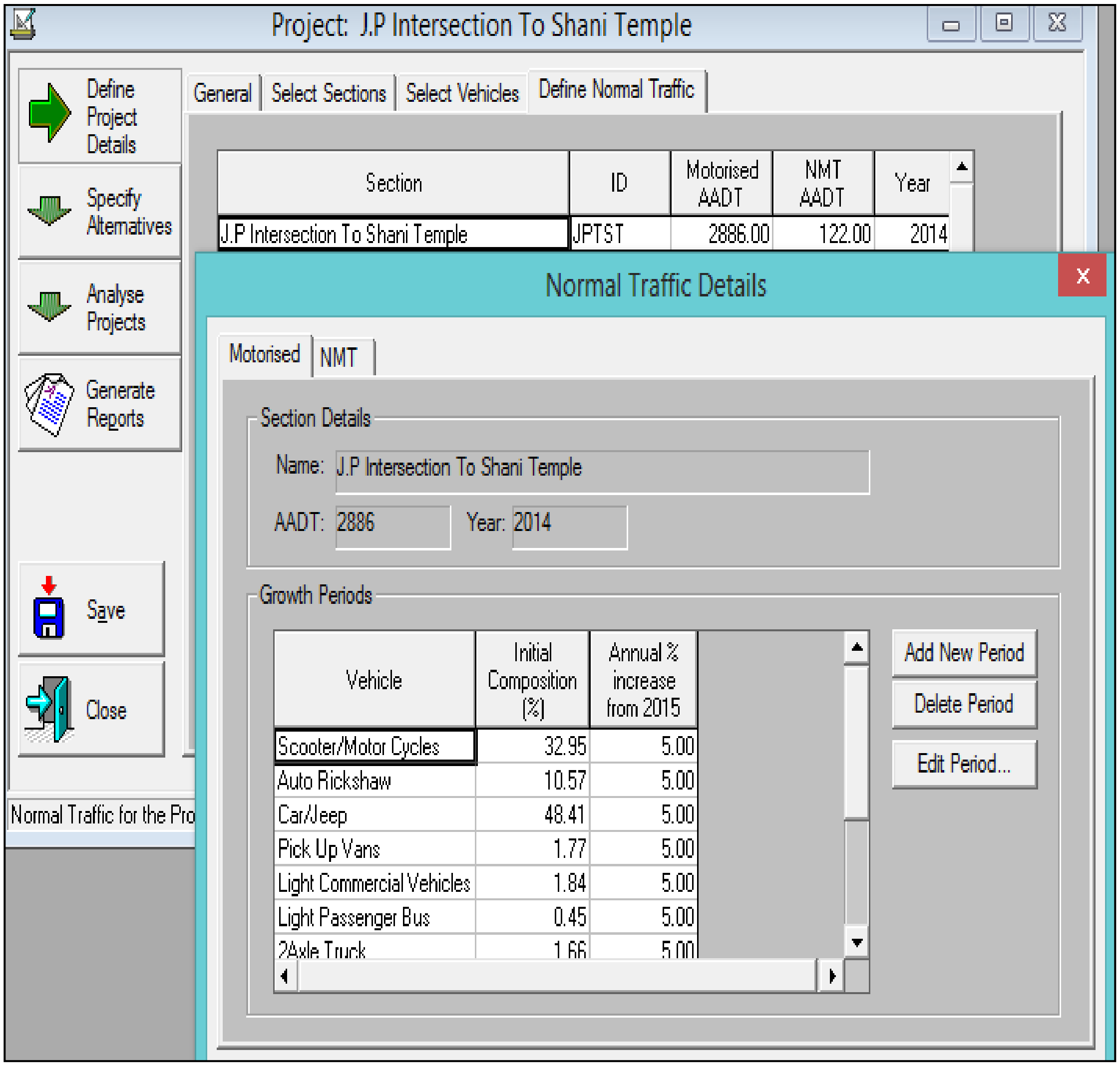


Figure 4.13: Identified Vehicle Category and its Growth Rate for the Project Analysis

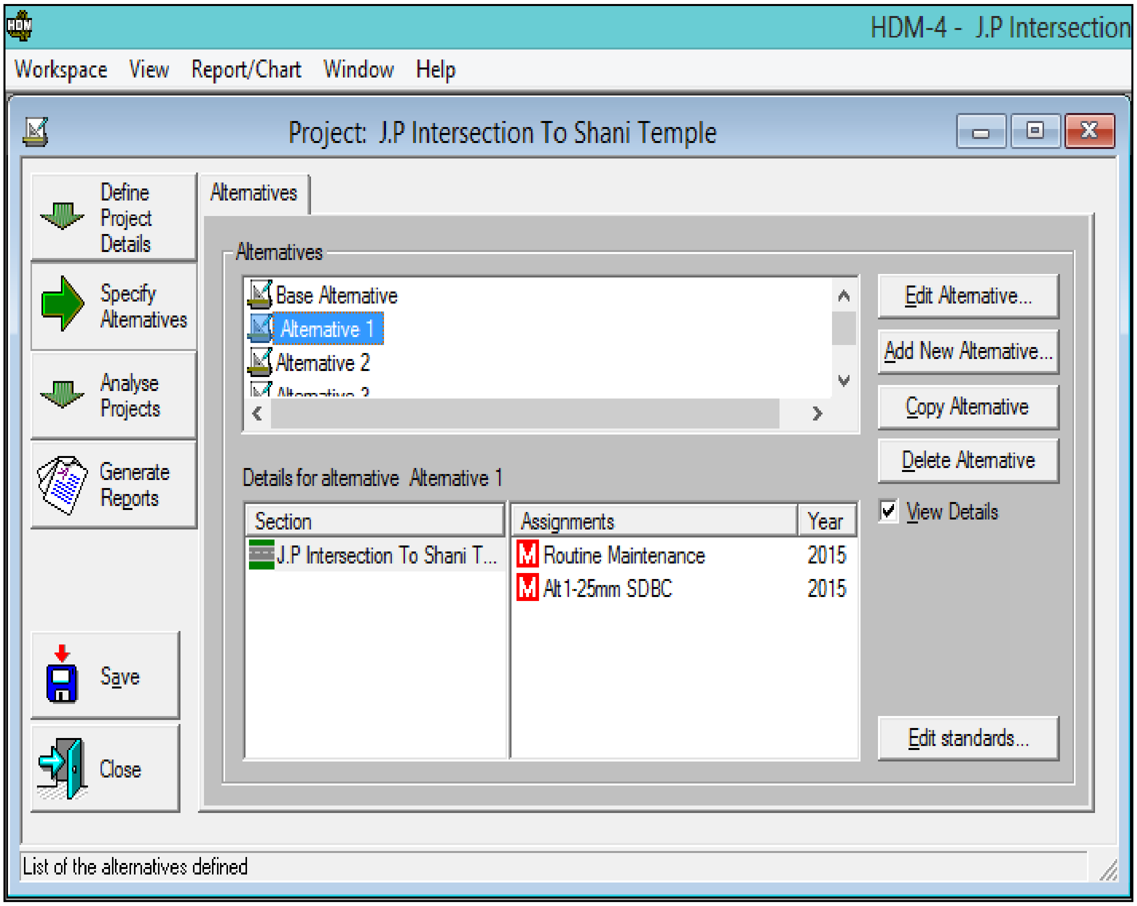


Figure 4.14: Specifiying alternatives for the project in HDM-4

Figure 4.15 present the Setup run tab as accessed via the Analyzing Project. This screen identifies the base project alternative selected for economic analysis (mostly routine maintenance alternative attached with the section) and the discount rate (in the present case it is 12%). The costs benefits analysis is done where base alternative is compared with the identified five different alternatives, as defined under Specify Alternatives/Alternatives.

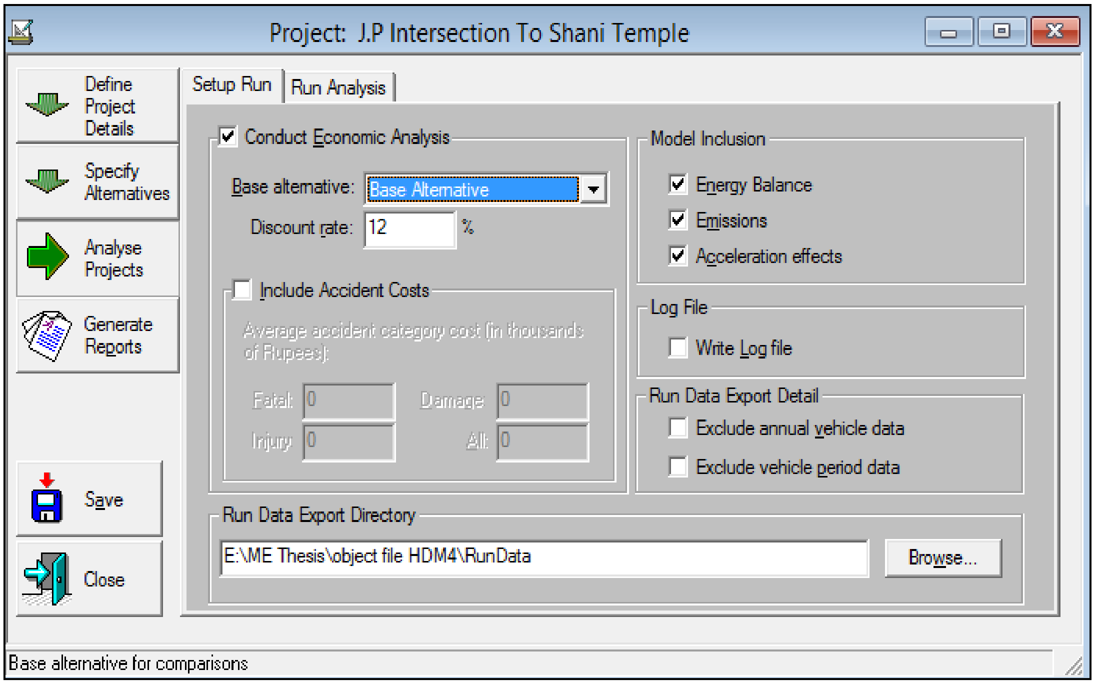


Figure 4.15: Analyzing The Project for Life Cycle Analysis

The costs benefits of optimum alternative are compared with those alternatives which have been defined under 'Alternatives'. For the present case study, accident costs, energy balance analysis, emissions calculations, and acceleration effects are not included in the analysis.

The various maintenance work items given in maintenance standards and interventions of their application are already mentioned in the maintenance work. The present thesis gives descriptions of the different works that have to be implemented in each year of the analysis period which is from year 2015-2034, under each maintenance strategy. The unit cost associated with each work item has been provided accordingly by looking into the departmental scheduled rates (DSR). The optimum Alternative is selected for both the cases (up and down carriageway) which are selected on the basis of Economic Internal Rate of Return (EIRR) which is presented in Figure 4.16.

HDM-4

HIGHWAY DEVELOPMENT & MANAGEMENT

Economic Indicators Summary

Study Name: J.P Intersection To Shani Temple
Run Date: 19-06-2014
Currency: Rupees (millions)
Discount Rate: 12.00%.

Alternative	Present Value of Total Agency Costs (RAC)	Present Value of Agency Capital Costs (CAP)	Increase in Agency Costs (C)	Decrease in User Costs (B)	Net Exogenous Benefits (E)	Net Present Value (NPV = B+E-C)	NPV/Cost Ratio (NPV/RAC)	NPV/Cost Ratio (NPV/CAP)	Internal Rate of Return (IRR)
Base Alternative	0.549	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Alternative 1	4.492	4.492	3.943	4.805	0.000	0.862	0.192	0.192	14.0 (1)
Alternative 2	8.569	8.569	8.020	5.580	0.000	-2.440	-0.285	-0.285	8.1 (1)
Alternative 3	8.753	8.753	8.204	5.108	0.000	-3.097	-0.354	-0.354	7.1 (1)
Alternative 4	14.920	14.920	14.371	5.965	0.000	-8.406	-0.563	-0.563	1.7 (1)
Alternative 5	8.062	8.062	7.513	4.504	0.000	-3.010	-0.373	-0.373	6.8 (1)

Figure in brackets is number of IRR solutions in range -90 to +900

Figure 4.16: Economic Indicators of Different Maintenance Alternatives for J.P Associate Office To Shani Temple

HDM-4

HIGHWAY DEVELOPMENT & MANAGEMENT

Economic Indicators Summary

Study Name: Shani Temple To J.P Intersection
Run Date: 14-07-2014
Currency: Rupees (millions)
Discount Rate: 12.00%.

Alternative	Present Value of Total Agency Costs (RAC)	Present Value of Agency Capital Costs (CAP)	Increase in Agency Costs (C)	Decrease in User Costs (B)	Net Exogenous Benefits (E)	Net Present Value (NPV = B+E-C)	NPV/Cost Ratio (NPV/RAC)	NPV/Cost Ratio (NPV/CAP)	Internal Rate of Return (IRR)
Base Alternative	0.550	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Alternative 1	4.492	4.492	3.942	4.418	0.000	0.476	0.106	0.106	13.1 (1)
Alternative 2	8.569	8.569	8.019	5.251	0.000	-2.768	-0.323	-0.323	7.4 (1)
Alternative 3	8.753	8.753	8.203	4.724	0.000	-3.479	-0.397	-0.397	6.2 (1)
Alternative 4	14.920	14.920	14.370	5.695	0.000	-8.675	-0.581	-0.581	0.8 (1)
Alternative 5	8.062	8.062	7.512	4.134	0.000	-3.378	-0.419	-0.419	5.9 (1)

Figure in brackets is number of IRR solutions in range -90 to +900

Figure 4.17: Economic Indicators of Different Maintenance Alternatives for Shani Temple to J.P. Associate Office

As per above Figure 4.16 which is the output of the project analysis identifies Alternative 1 as the optimum maintenance alternative since it has got the maximum EIRR as economic indicators. This maintenance alternative is for study section J.P. Associate Office to Shani Temple which is also displayed in the Figure.

Similarly the same process is to repeated for the opposite carriageway identified as Shani Temple to J.P. Associate Office and vehicle fleet has to be pre-defined in the Vehicle Fleet folder under the same name. Vehicles types to be used for the analysis are selected under the Select Section and Select Vehicle Tabs respectively, as discussed above.

Figure 4.17 also identifies maintenance Alternative 1 for opposite carriageway which is Shani Temple to J.P. Associate Office.

CHAPTER 5

ANALYSIS AND DISCUSSION

5.1 General

HDM-4 road deterioration models have a number of adjustment factors / parameters and it is important to acknowledge the general level of sensitivity of the model to each parameter. It is very difficult to acknowledge each parameter for sensitivity analysis due to insufficient data which is generally obtained through time series observations for road structural and functional variables. Accordingly 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 nature of the parameter, the result being considered, and the values assigned to other parameters for a given analysis. The sensitivity of results to variations in a parameter therefore varies somewhat under different circumstances. Therefore ccalibration of HDM-4 distress deterioration models improves the accuracy of predicted pavement performance. The pavement deterioration models incorporated in HDM-4 were developed from results of large field experiments conducted in several countries. Consequently, the default equations in HDM-4 if used without calibration, would predict pavement performance that may not accurately match that observed on specific road sections. A fundamental assumption made prior of using HDM-4 is that the pavement performance models needs to be calibrated to reflect the observed rates of pavement deterioration on the roads where the models are applied.

5.2 Background of Project analysis

Project analysis has been used in the present thesis to find the sensitivity of calibration parameter for distress cracking which includes initiation and progression both. The entire field and laboratory data are used as input to HDM-4 making project case for Up and Down carriageway viz. Shani Temple to J.P. Associate Office and J.P. Associate Office to Shani Temple. The traffic volume survey data, weather and environmental conditions, road construction and maintenance history, road distress data, road geometric data, etc. have been used to create a project for life cycle analysis by providing appropriate maintenance and rehabilitation alternatives. The project was made to run using HDM-4 for 20 years of design life period and the optimized alternative was selected based on economic indicators which are having highest Economic Internal Rate of Return (EIRR).

5.3 Discussions with respect to Default Calibration Factor

During set up of the project analysis, the base maintenance alternative is kept as minimum maintenance required for design life of the study sections and economic analysis is to be carried out with a discount rate of 12%. While executing the project analysis keeping as default calibration factor as 1 for all distress deterioration models, Alternative 1, Alternative 2, Alternative 3, Alternative 4 and Alternative 5 are compared against the Base Alternative. As a result of this process, the pavement deterioration reports and the maintenance works reports are generated, for all maintenance strategies considered in previous Chapter. Figure 5.1 and Figure 5.2 presents the average roughness for all alternatives having default value as 1 in the models.

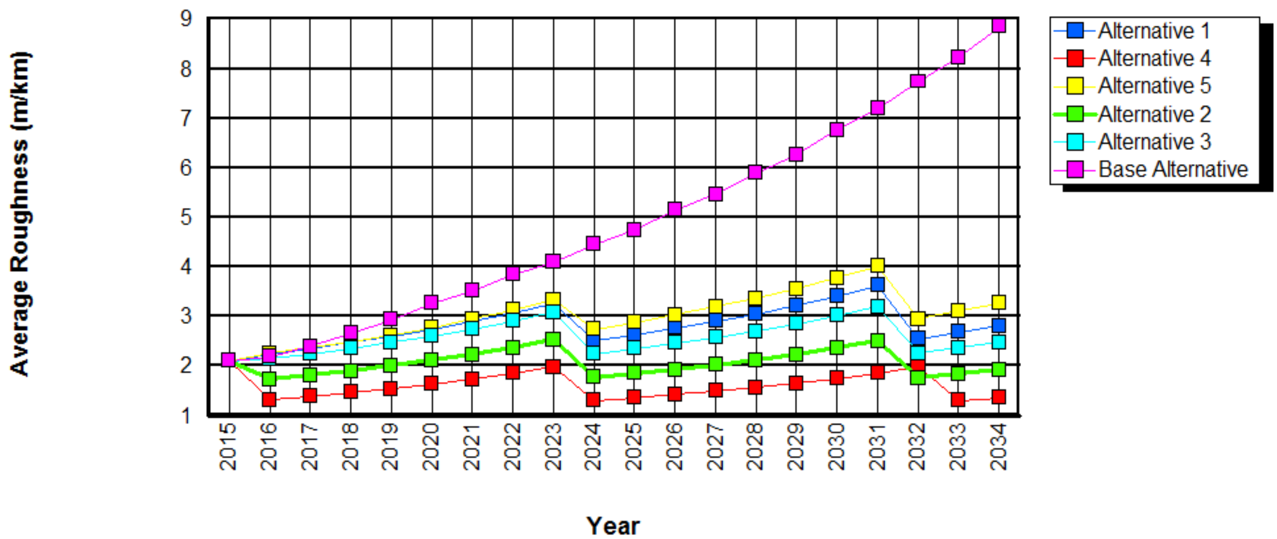


Figure 5.1: Average Roughness of Carriageway J.P. Associate Office to Shani Temple

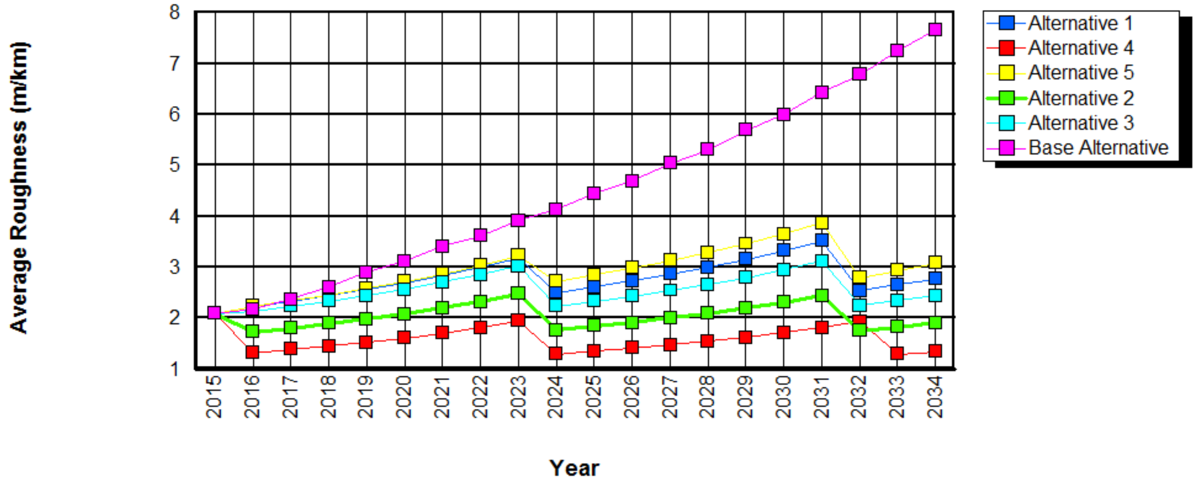


Figure 5.2: Average Roughness of Carriageway Shani Temple to J.P. Associate Office

From the above figures it is quite clear that the road deterioration is faster in the case of J.P. Associate Office to Shani Temple than Shani Temple to J.P. Associate Office. This has been observed by looking into the life cycle analysis for the base case where work items included into maintenance intervention is common for both the cases. Since other alternatives have common intervention criteria which are 15 percent cracked area before application therefore in both the cases the intervention years and roughness limits are common. It is not possible to select the optimized maintenance alternative from the above graphs visually and without analyzing the economic indicators against different maintenance alternatives.

The deterioration reports and graphical representations of the road study sections, as obtained under all alternative maintenance strategies for analysis period of 20 years are given in Table 5.1 to Table 5.2 and Figure 5.3 to Figure 5.8. Pavement distresses such as roughness, cracking and rut-depth show annual controlled progression over the analysis period.

Figure 5.3 presents the average cracking area for J.P Associate Office to Shani Temple having default value as 1 in the models.

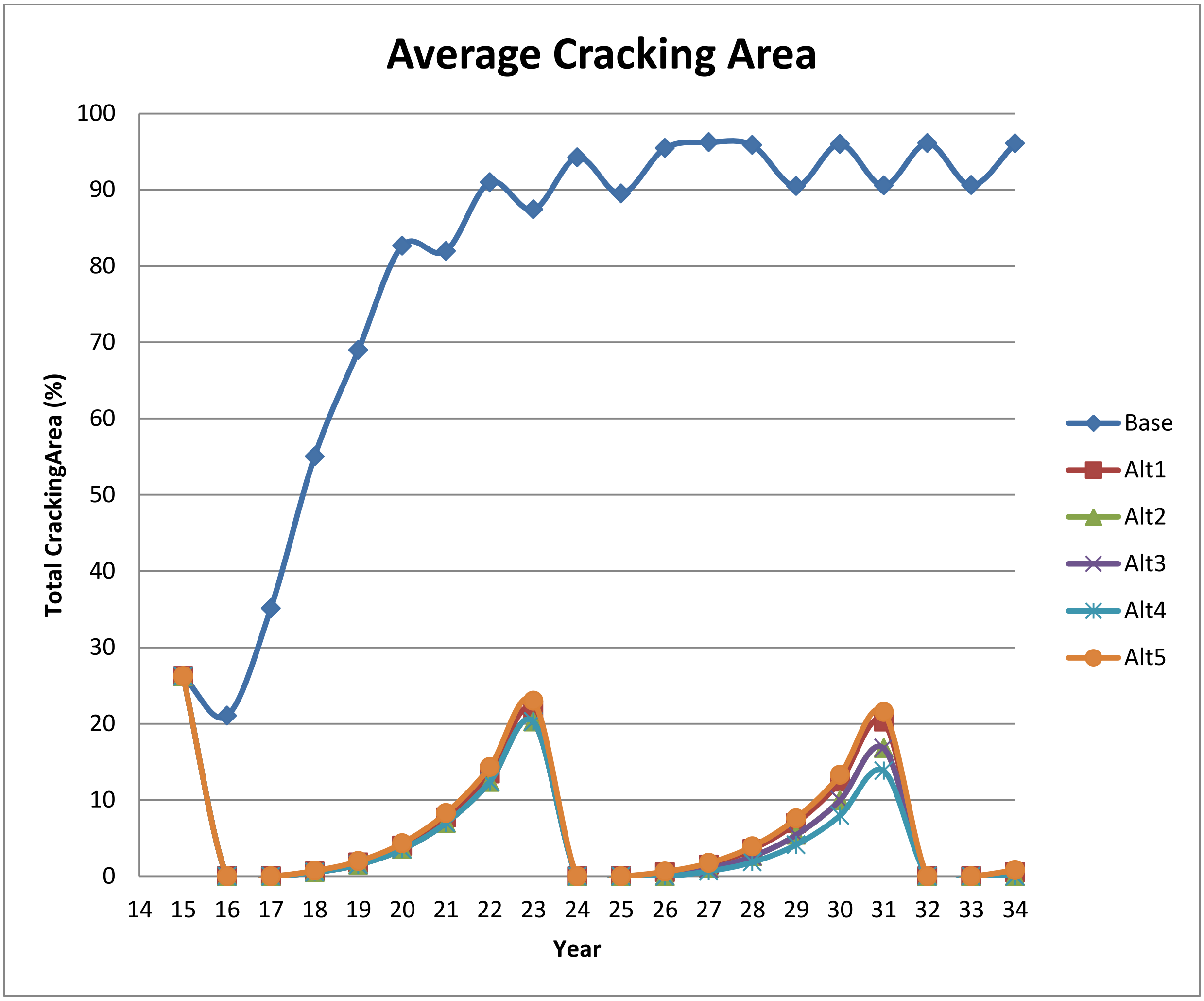


Figure 5.3: Average Cracking of Carriageway J.P. Associate Office to Shani Temple

Table 5.1: Road Deterioration Range for Different Alternatives between J.P. Associates Office to Shani Temple

Alternative	Year		Roughness	Total Cracking	Mean Rut Depth
Base Alternative	2015	Before	2.11	26.22	5.41
		After	2.09	11.58	5.51
	2023	Before	4.28	87.39	9.58
		After	4.28	87.39	9.58
Alternative 1	2015	Before	2.19	26.22	5.41
		After	2.19	0.00	0.81
	2023	Before	2.04	21.77	3.86
		After	2.04	0.00	0.58
Alternative 2	2015	Before	2.19	26.22	5.41
		After	1.69	0.00	0.81
	2023	Before	2.62	20.25	3.44
		After	1.73	0.00	0.52
Alternative 3	2015	Before	2.19	26.22	5.41
		After	2.09	0.00	0.81
	2023	Before	3.19	20.43	3.69
		After	2.19	0.00	0.55
Alternative 4	2015	Before	2.19	26.22	5.41
		After	1.28	0.00	0.81
	2023	Before	2.06	20.25	3.24
		After	1.27	0.00	0.49
Alternative 5	2015	Before	2.19	26.22	5.41
		After	2.19	0.00	0.81
	2023	Before	3.46	22.97	4.02
		After	2.67	0.00	0.60

Table 5.2: Road Deterioration Range for Different Alternatives between Shani Temple to J.P. Associates Office

Alternative	year		Roughness	Total Cracking	Mean Rut Depth
Base Alternative	2015	Before	2.18	26.22	5.40
		After	2.08	11.58	5.40
	2023	Before	4.06	92.62	9.46
		After	3.97	77.91	9.58
Alternative 1	2015	Before	2.19	26.22	5.41
		After	2.19	0.00	0.81
	2013	Before	3.38	21.77	3.86
		After	2.45	0.00	0.58
	2015	Before	2.19	26.22	5.41

Alternative 2		After	1.69	0.00	0.81
	2023	Before	2.62	20.25	3.44
		After	1.73	0.00	0.52
Alternative 3	2015	Before	2.19	26.22	5.41
		After	2.09	0.00	0.81
	2023	Before	3.19	20.43	3.69
		After	2.19	0.00	0.55
Alternative 4	2015	Before	2.19	26.22	5.41
		After	1.28	0.00	0.81
	2023	Before	2.06	20.25	3.24
		After	1.27	0.00	0.49
Alternative 5	2015	Before	2.19	26.22	5.41
		After	2.19	0.00	0.81
	2023	Before	3.46	22.47	4.02
		After	2.67	0.00	0.60

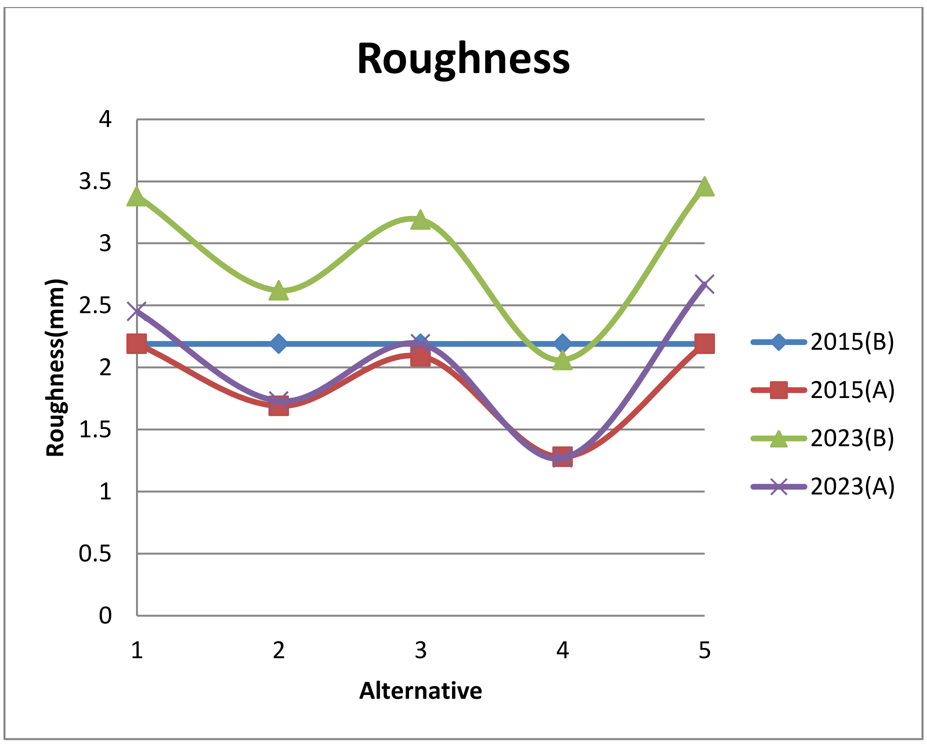


Figure 5.4: Road Roughness Range for Different Alternatives for J.P. Associates Office to Shani Temple

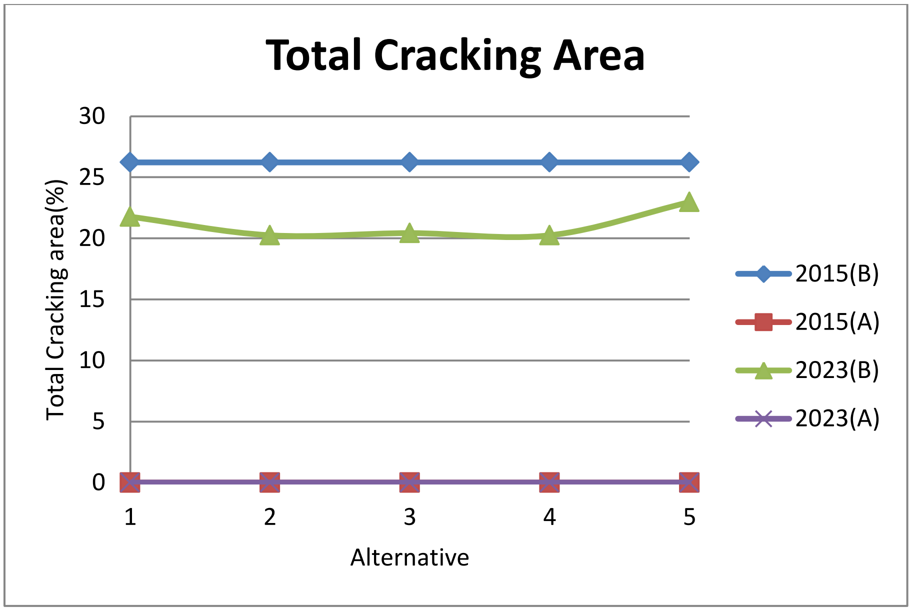


Figure 5.5: Cracking Range for Different Alternatives for J.P. Associates Office to Shani Temple

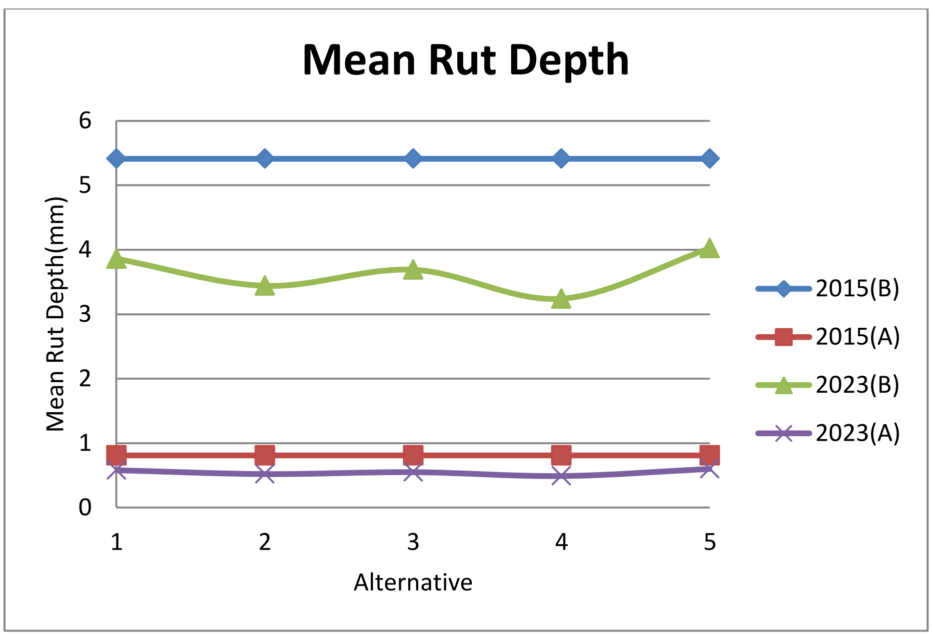


Figure 5.6: Rutting Range for Different Alternatives for J.P. Associates Office to Shani Temple

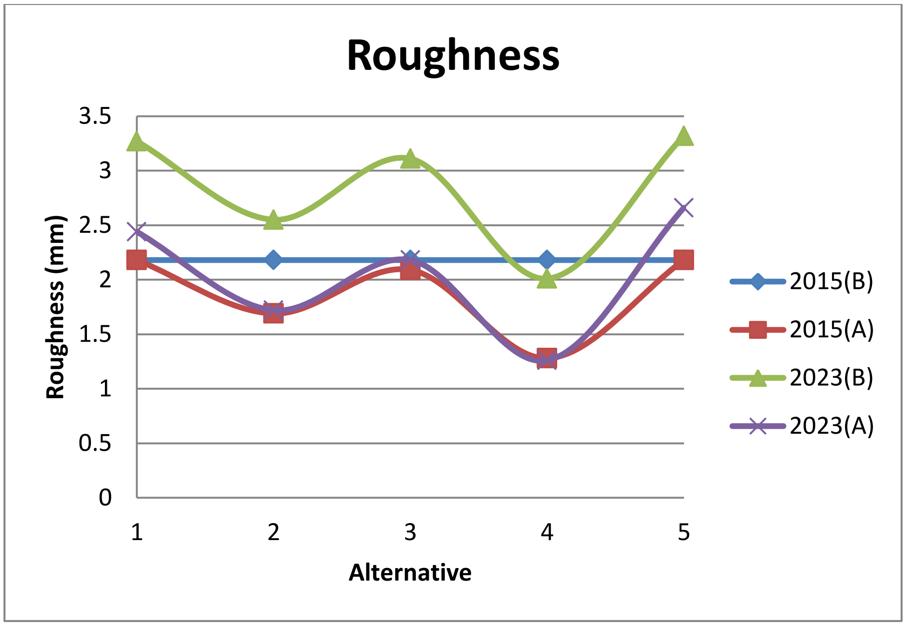


Figure 5.7: Road Roughness Range for Different Alternatives for Shani Temple to J.P. Associates Office

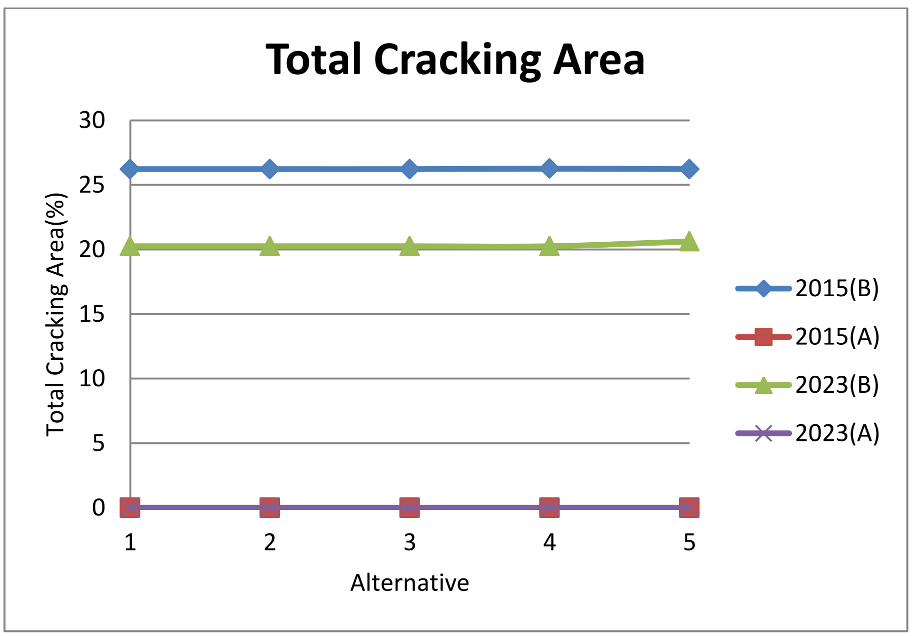


Figure 5.8: Cracking Range for Different Alternatives for Shani Temple to J.P. Associates Office

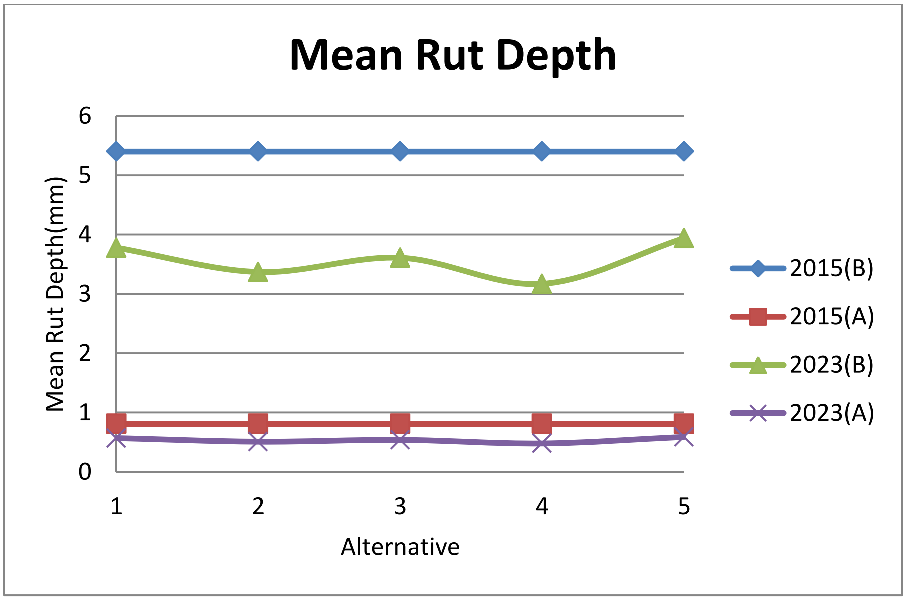


Figure 5.9: Rutting Range for Different Alternatives for Shani Temple to J.P. Associates Office

The road distress deterioration pattern with respect to roughness, cracking and rutting under default calibration of 1 for the study sections models for local conditions are different under different maintenance strategies.

HDM-4 roughness model contains rut depth component whereas most of the Indian model does not contain any such component for bituminous surfacing, which is probably indicative of the fact that rutting is not very pronounced on Indian roads. It is mainly because of the poor lane discipline of the moving commercial vehicles and also because of superior quality of bituminous surfacing. Moreover, maximum amount of rutting develops within first year of construction/reconstruction of the pavement because of initial densification of base course and sub-base courses, and in the subsequent years the rate of rut depth progression recedes considerably. Therefore, for calibration of roughness model for existing pavements, the rutting component of HDM-4 may be set to zero. Rutting failure is generally limited to weak quality control or under design pavement structure.

The Indian Roughness model contains a separate patching component but the HDM-4 model does not contain any such exclusive component as patching into the model and is not considered a distress in HDM-4 system. Instead, the effect of pothole patching is included in the pothole component itself.

5.4 Discussions with respect to Different Calibration Factor

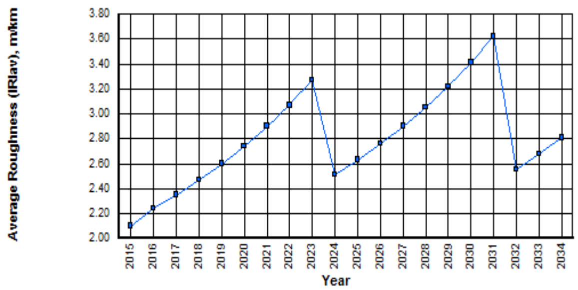
To find the optimized maintenance alternative for life cycle analysis, it is essential to analyze the outputs with respect to economic indicators. After providing essential and realistic inputs obtained from primary and secondary data, the project output were economically analyzed and was found that Alternative 1 was having highest EIRR with respect to other alternatives. Though it was not much higher than the given discount rate of 12% but maintenance Alternative 1 was feasible economically.

Since alternative 1 (surfacing by 25mm SDBC) had the highest EIRR for both the cases under default value of common calibration factor as 1, therefore the default calibration factor 1 was varied by increment of 0. 1 ranging from 0.7 to 1.3 for roughness as well as cracking initiation and progression.

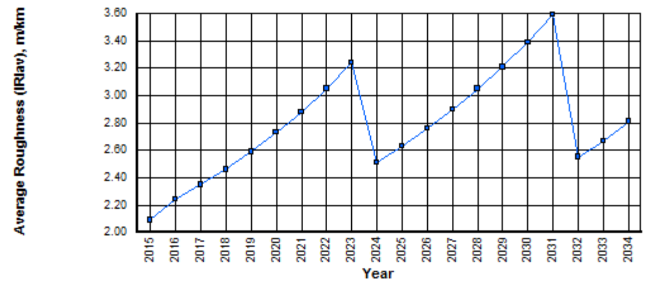
5.4.1 Effect on Average Roughness with Different Calibration Factors

Average roughness is considered to be the most useful indicator of the pavement deterioration, or average condition of the pavement section at any given point of time. The effect of roughness progression (average roughness) on maintenance works to be carried out with respect to specific year under maintenance strategy with Alternative 1 for selected study sections with varying calibration factors are presented in Figure 5.9 and Table 5.3 for carriageway J.P. Associate Office Intersection to Shani Temple and Figure 5.10 and Table 5.4 for carriageway Shani Temple to J.P. Associates Office Intersection respectively. The inbuilt equation for roughness progression where the calibration factor is used is shown in Annexure 5.

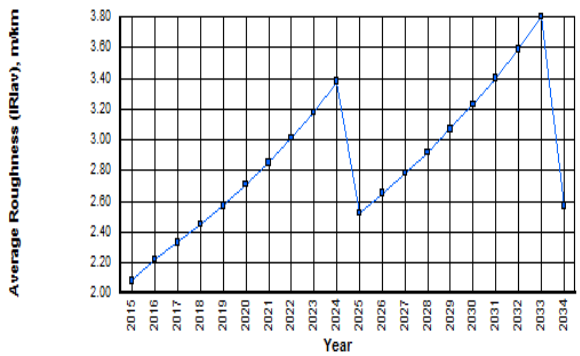
Calibration factor =1



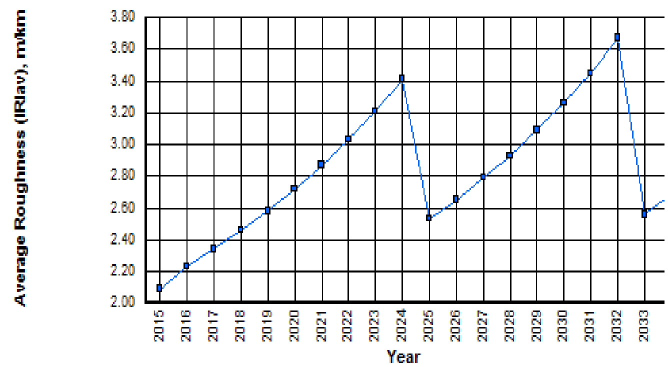
Calibration factor =0.9



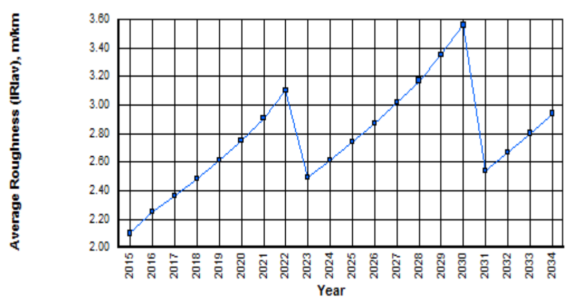
Calibration Factor =0.8



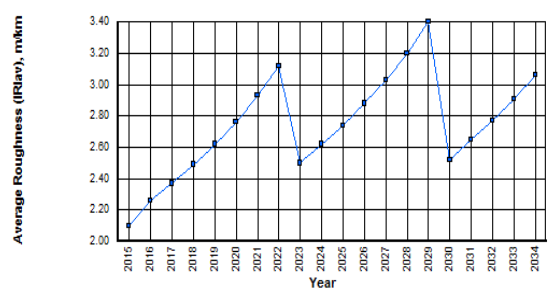
Calibration Factor =0.7



Calibration factor =1.1



Calibration factor =1.2



Calibration Factor =1.3

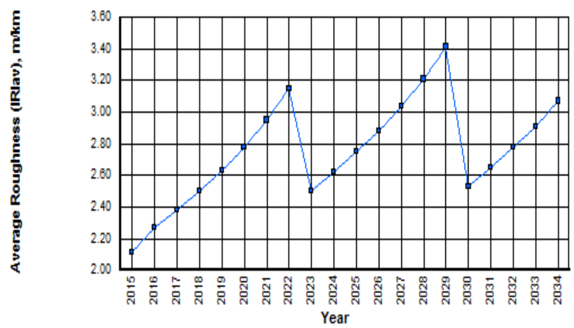


Figure 5.10: Typical View of Roughness Progression with Different Calibration Factors for Shani Temple to J.P.Associate Office

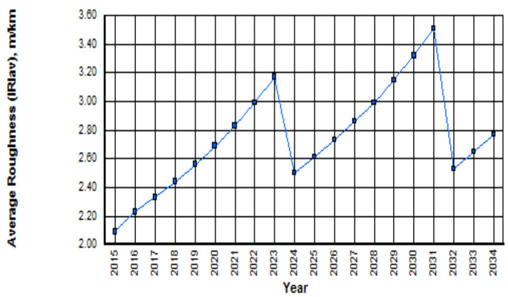
Table 5.3: Maintenance Application Years with Changing Calibration Factors for Roughness Progression for Shani Temple to J.P. Associate Office

Calibration Factor	Year	Maintenance Application
1.3	2022	Maintenance Provided
	2029	Maintenance Provided
1.2	2022	Maintenance Provided
	2029	Maintenance Provided
1.1	2022	Maintenance Provided
	2030	Maintenance Provided
1	2023	Maintenance Provided
	2031	Maintenance Provided
0.9	2023	Maintenance Provided
	2031	Maintenance Provided
0.8	2024	Maintenance Provided
	2032	Maintenance Provided
0.7	2024	Maintenance Provided
	2033	Maintenance Provided

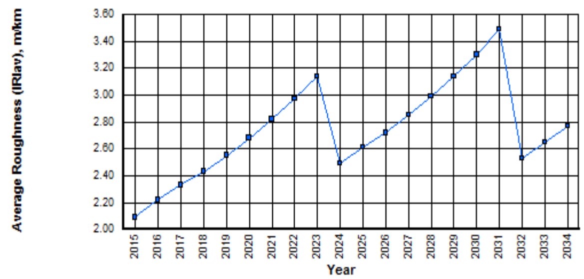
The progression of roughness triggers maintenance alternative 1 at specific year when it reaches to intervention levels according to the specified intervention criteria. It has being observed from the above Table 5.3 that increases in calibration factors from 0.7 to 1.3, the maintenance alternative intervenes early viz. one year before. For example maintenance alternative 1 is triggered in the year 2022 for calibration factor 1.3 and triggered in the year 2024 for calibration factor 0.7.

The same pattern has been found for carriageway Shani Temple to J.P. Associates Office Intersection and presented in Figure 5.10 and Table 5.4.

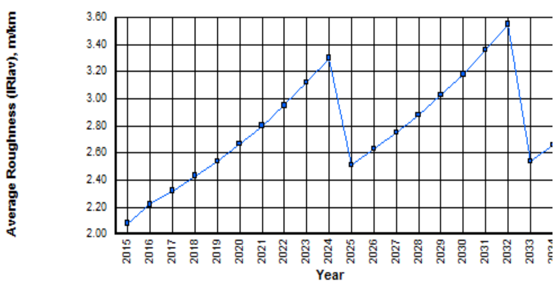
Calibration factor =1



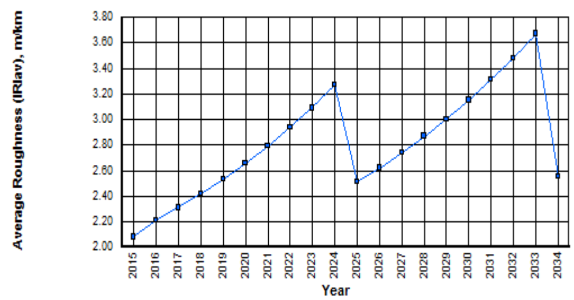
Calibration factor =0.9



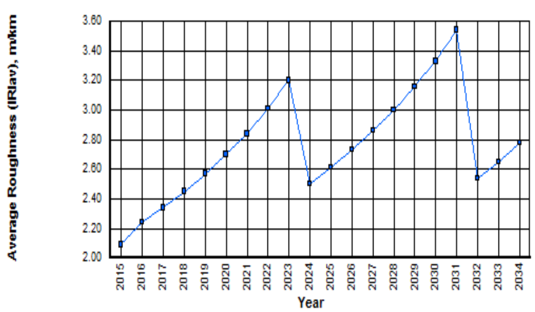
Calibration Factor =0.8



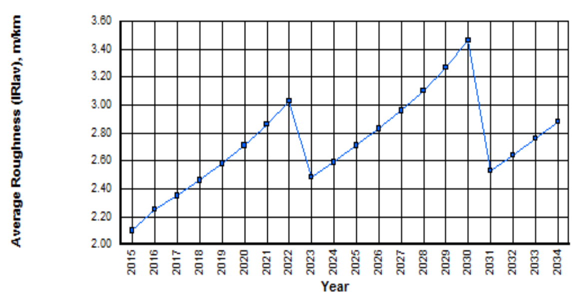
Calibration Factor =0.7



Calibration factor =1.1



Calibration factor =1.2



Calibration Factor =1.3

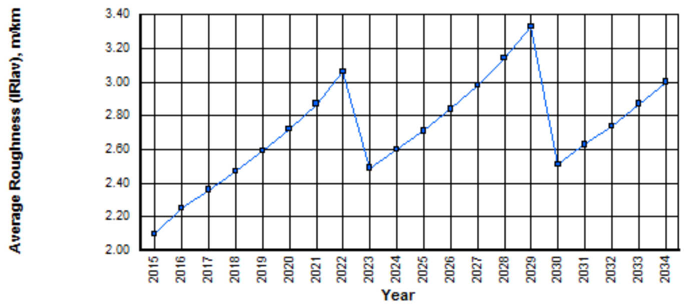


Figure 5.11: Typical View of Roughness Progression with Different Calibration Factors for J.P. Associate Office to Shani Temple

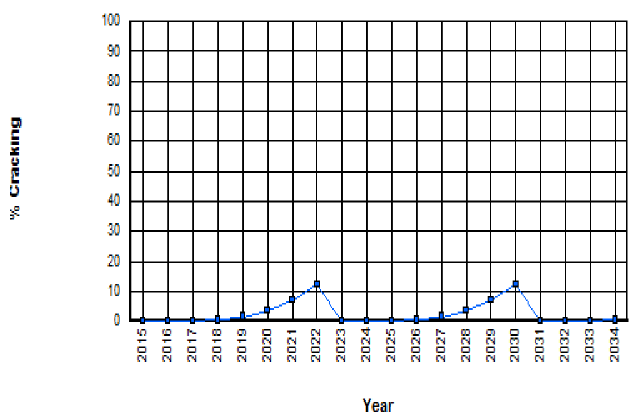
Table 5.4: Maintenance Application Years with Changing Calibration Factors Roughness Progression for J.P. Associate Office to Shani Temple

Calibration Factor	Year	Maintenance Application
1.3	2022	Maintenance Provided
	2029	Maintenance Provided
1.2	2022	Maintenance Provided
	2030	Maintenance Provided
1.1	2023	Maintenance Provided
	2031	Maintenance Provided
1	2023	Maintenance Provided
	2031	Maintenance Provided
0.9	2023	Maintenance Provided
	2031	Maintenance Provided
0.8	2024	Maintenance Provided
	2032	Maintenance Provided
0.7	2024	Maintenance Provided
	2033	Maintenance Provided

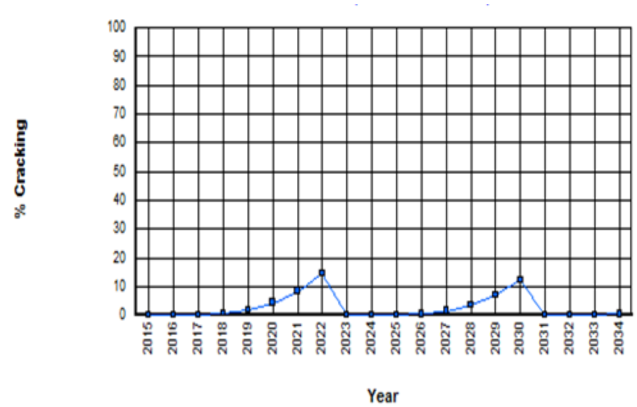
5.4.2 Effect on Average Cracking with Different Calibration Factors

Average Cracking is considered to be the most useful indicator of the pavement deterioration, or average condition of the pavement section at any given point of time. The effect of cracking initiation and progression on maintenance works to be carried out with respect to specific year under maintenance strategy with Alternative 1 for selected study sections with varying calibration factors are presented in Figure 5.11 and Table 5.4 for carriageway Shani Temple to J.P. Associate Office for initiation and Figure 5.12 and Table 5.5 for same carriageway in case of progression. The inbuilt equation for cracking initiation and progression where the calibration factor is used is shown in Annexure 6 and Annexure 7 respectively.

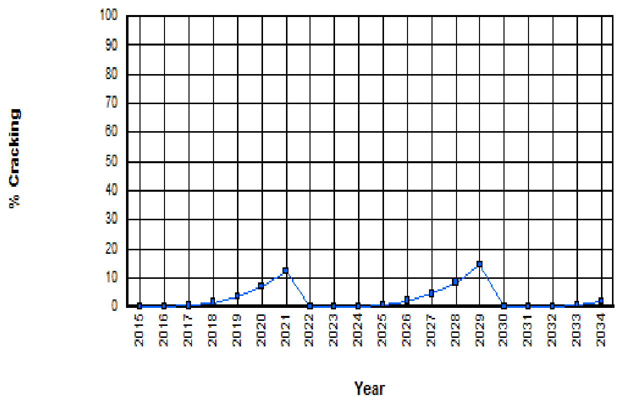
Calibration factor =1



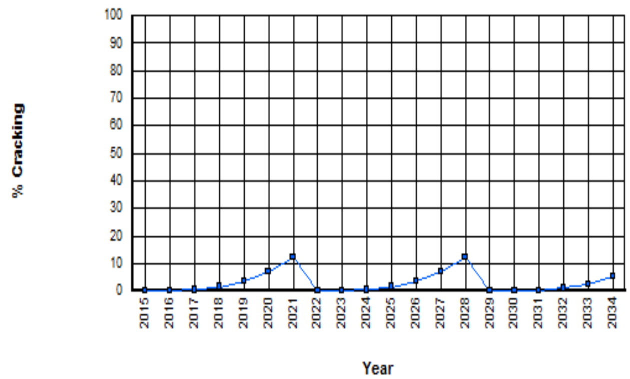
Calibration factor =0.9



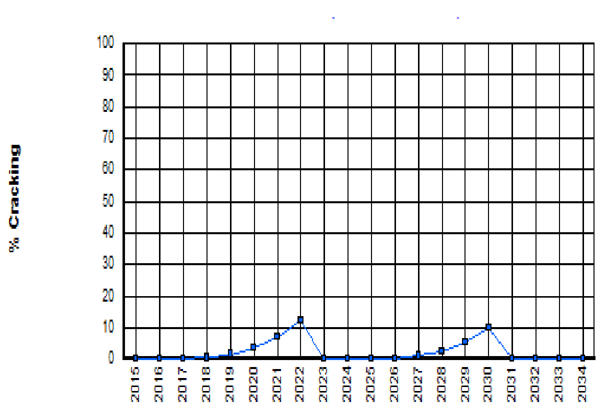
Calibration Factor =0.8



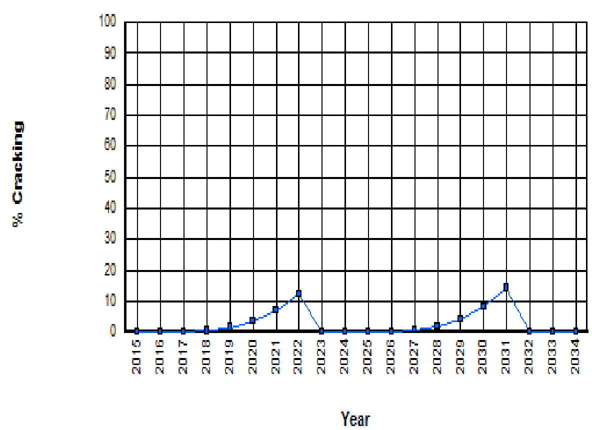
Calibration Factor =0.7



Calibration factor =1.1



Calibration factor =1.2



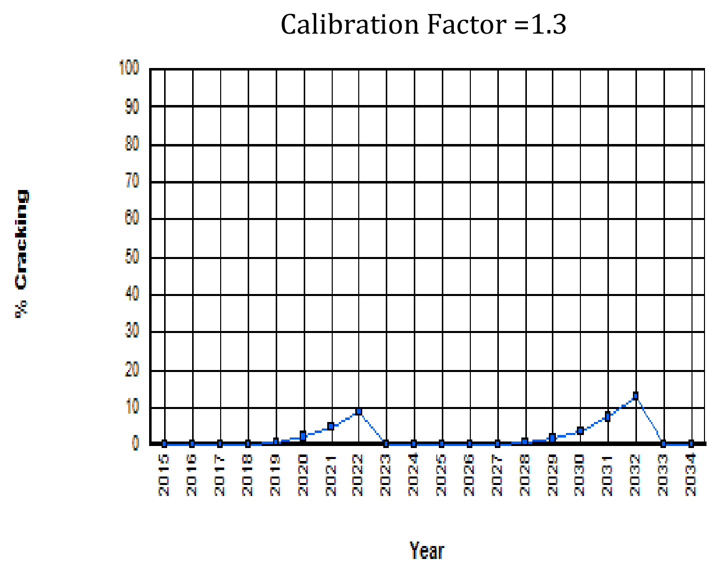


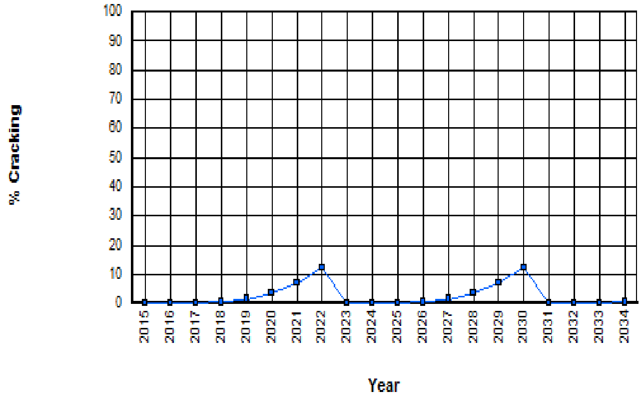
Figure 5.12: Typical View of Cracking Initiation with Different Calibration Factors for Shani Temple to J.P.Associate Office

Table 5.5: Maintenance Application Years with Changing Calibration Factors for Cracking Initiation for Shani Temple to J.P. Associate Office

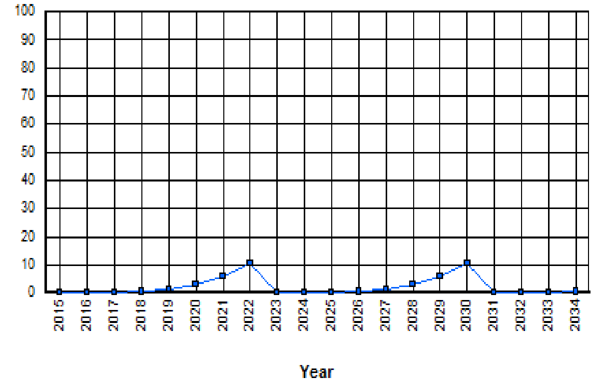
Calibration Factor	Year	
	2020	Crack Started
	2022	Maintainance provided
	2029	Crack Started
1.3	2032	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2028	Crack Started
1.2	2031	Maintainance provided
1.1	2019	Crack Started

	2022	Maintainance provided
	2027	Crack Started
	2030	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2027	Crack Started
1	2030	Maintainance provided
	2019	Crack Started
0.9	2022	Maintainance provided
	2027	Crack Started
	2030	Maintainance provided
	2018	Crack Started
	2021	Maintainance provided
	2026	Crack Started
0.8	2029	Maintainance provided
	2018	Crack Started
	2021	Maintainance provided
	2025	Crack Started
	2028	Maintainance provided
	2032	Crack Started
0.7	2034	Maintainance provided

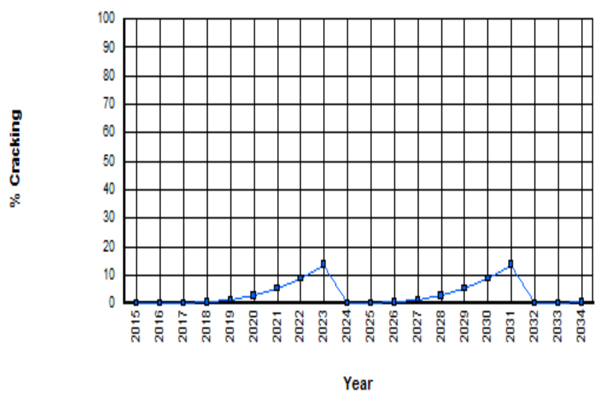
Calibration factor =1



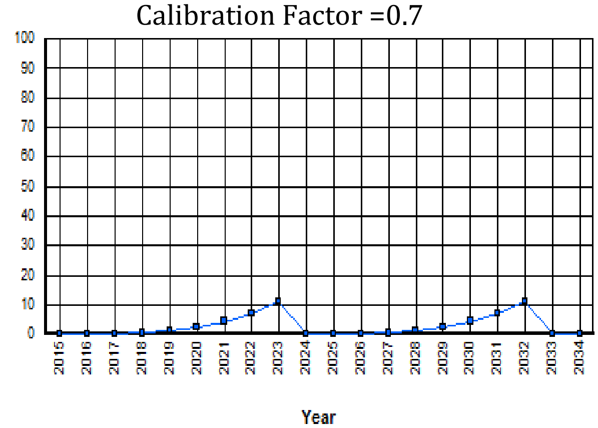
Calibration factor =0.9



Calibration Factor =0.8



Calibration Factor =0.7



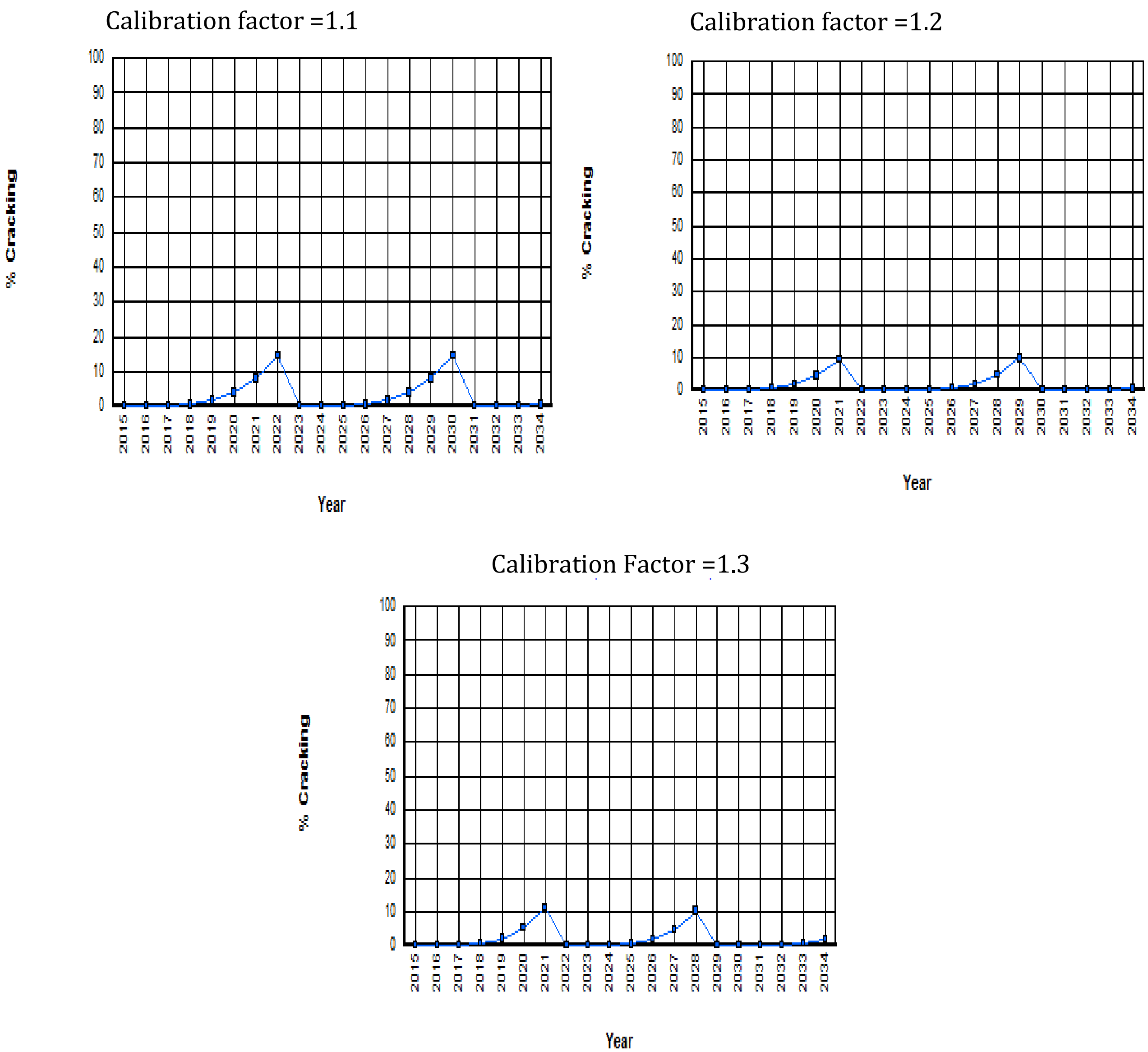


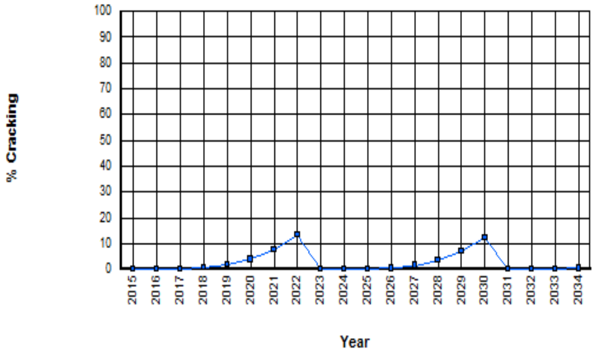
Figure 5.13: Typical View of Cracking Progression with Different Calibration Factors for Shani Temple to J.P. Associate Office

Table 5.6: Maintenance Application Years with Changing Calibration Factors for Cracking Progression for Shani Temple to J.P. Associate Office

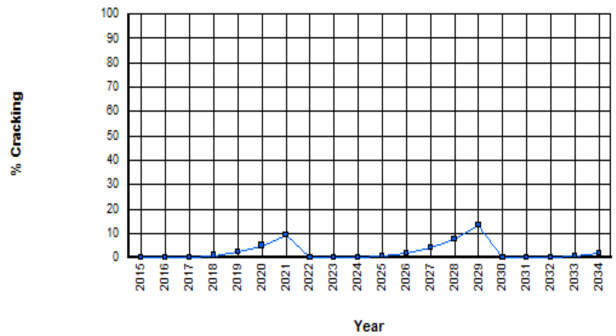
Calibration Factor	Year	
	2019	Crack Started
	2021	Maintainance provided
	2026	Crack Started
1.3	2028	Maintainance provided
	2019	Crack Started
	2021	Maintainance provided
	2027	Crack Started
1.2	2029	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2027	Crack Started
1.1	2030	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2027	Crack Started
1	2030	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2027	Crack Started
0.9	2030	Maintainance provided
	2019	Crack Started
	2023	Maintainance provided
	2027	Crack Started
0.8	2031	Maintainance provided
	2019	Crack Started
	2023	Maintainance provided
	2028	Crack Started
0.7	2032	Maintainance provided

Varying calibration factors are presented in Figure 5.13 and Table 5.7 for carriageway J.P. Associate Office to Shani Temple for initiation and Figure 5.14 and Table 5.8 for same carriageway in case of progression.

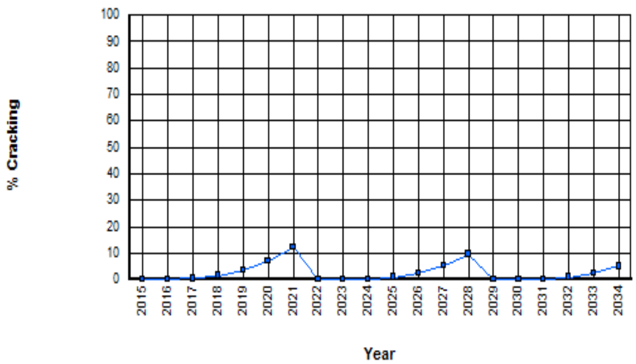
Calibration factor =1



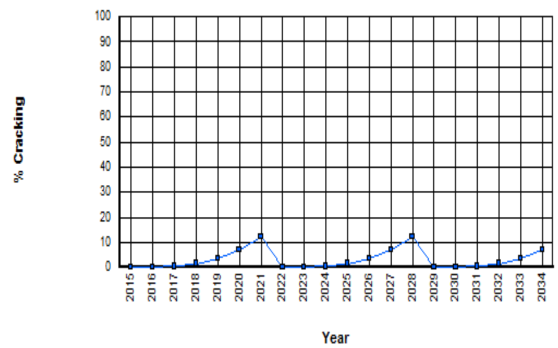
Calibration factor =0.9



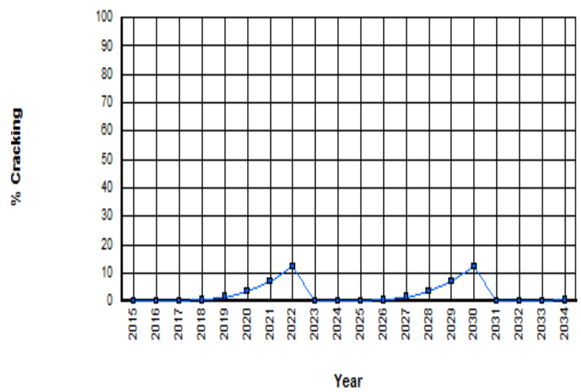
Calibration Factor =0.8



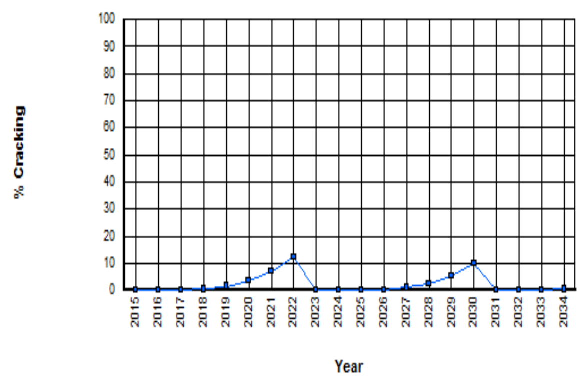
Calibration Factor =0.7



Calibration factor =1.1



Calibration factor =1.2



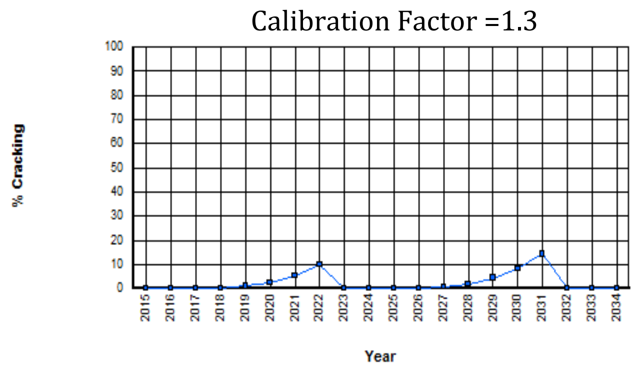


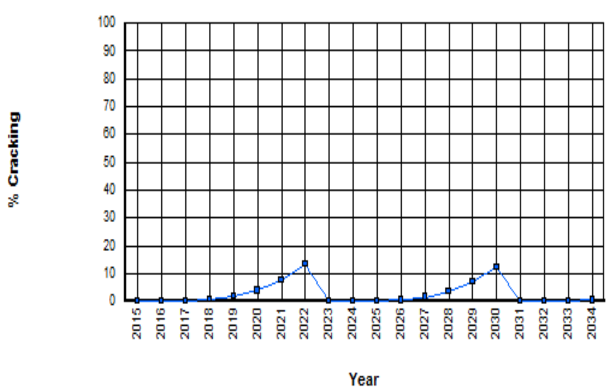
Figure 5.14: Typical View of Cracking Initiation with Different Calibration Factors for J.P. Associate Office to Shani Temple

Table 5.7: Maintenance Application Years with Changing Calibration Factors Cracking Initiation for J.P. Associate Office to Shani Temple

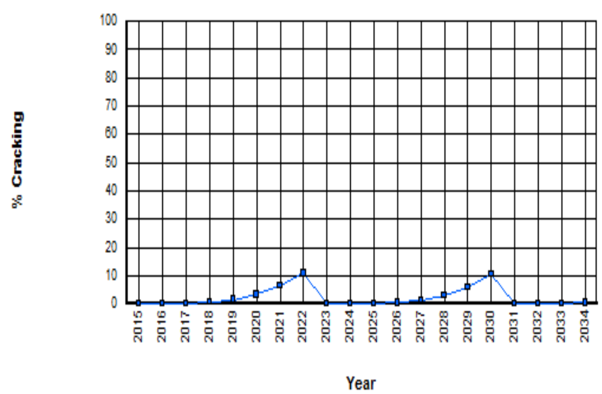
Calibration Factor	Year	
	2019	Crack Started
	2022	Maintainance provided
	2028	Crack Started
1.3	2031	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2027	Crack Started
1.2	2030	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2027	Crack Started
1.1	2030	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2027	Crack Started
1	2030	Maintainance provided

	2019	Crack Started
	2021	Maintainance provided
	2026	Crack Started
0.9	2029	Maintainance provided
	2018	Crack Started
	2021	Maintainance provided
	2026	Crack Started
	2028	Maintainance provided
	2032	Crack Started
0.8	2034	Maintainance provided
	2018	Crack Started
	2021	Maintainance provided
	2025	Crack Started
	2028	Maintainance provided
	2032	Crack Started
0.7	2034	Maintainance provided

Calibration factor =1



Calibration factor =0.9



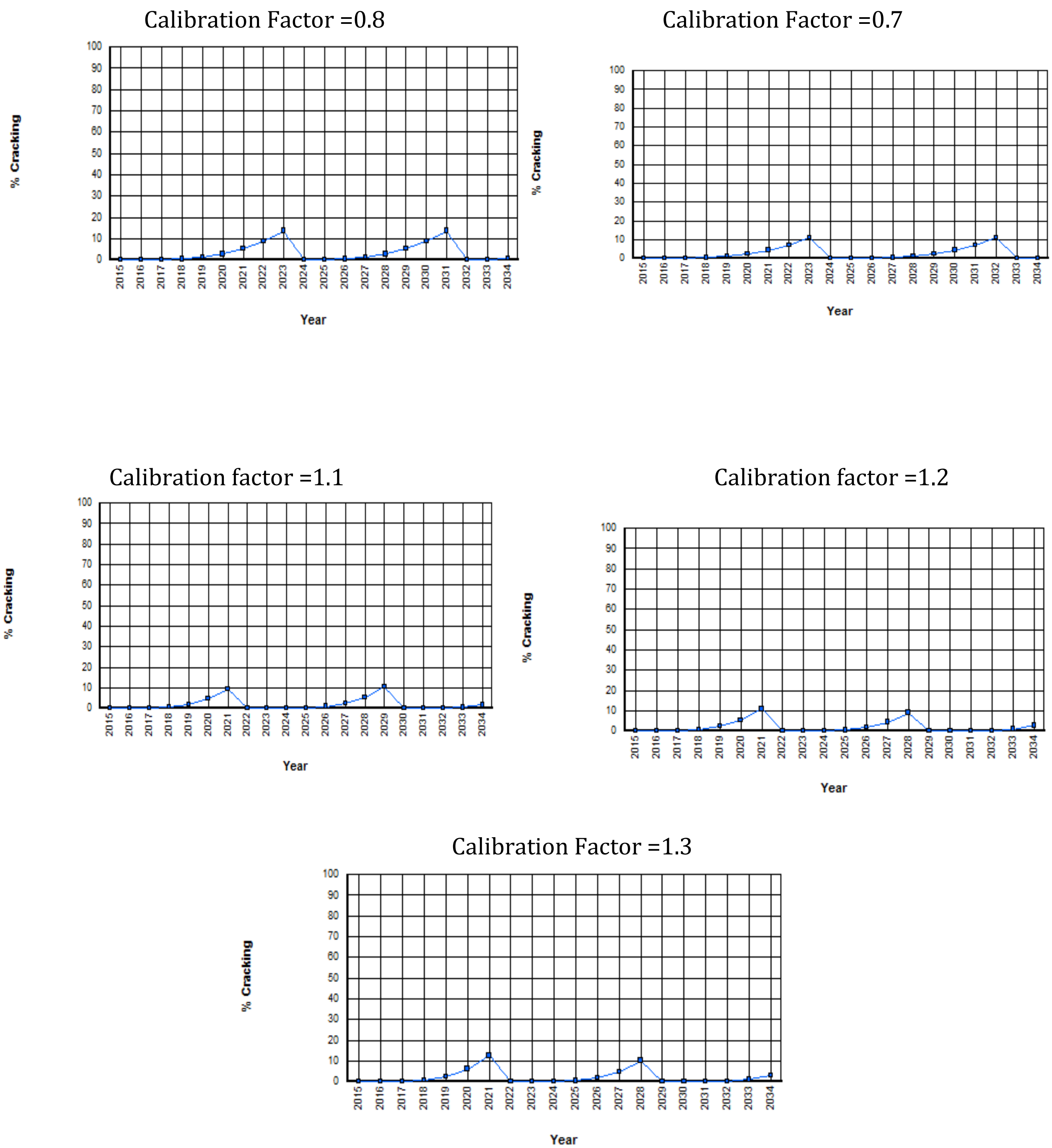


Figure 5.15: Typical View of Cracking Progression with Different Calibration Factors for J.P. Associate Office to Shani Temple

Table 5.8: Maintenance Application Years with Changing Calibration Factors Cracking Progression for J.P. Associate Office to Shani Temple

Calibration Factor	Year	
	2018	Crack Started
	2021	Maintainance provided
	2026	Crack Started
1.3	2028	Maintainance provided
	2018	Crack Started
	2021	Maintainance provided
	2026	Crack Started
1.2	2028	Maintainance provided
	2018	Crack Started
	2021	Maintainance provided
	2026	Crack Started
1.1	2029	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2027	Crack Started
1	2030	Maintainance provided
	2019	Crack Started
	2022	Maintainance provided
	2027	Crack Started
0.9	2030	Maintainance provided
	2019	Crack Started
	2023	Maintainance provided
	2027	Crack Started
0.8	2031	Maintainance provided
	2019	Crack Started
	2023	Maintainance provided
	2028	Crack Started
0.7	2032	Maintainance provided

5.5 Effect on EIRR with Respect to Crack Initiation and Progression

The economic indicators obtained from varying calibration factors for crack initiation and progression for both the carriageways under study sections are given in Figure 5.11 and Figure 5.12. Effect of Alternative 1 with varying calibration factors were analyzed with respect to default calibration factor of 1. It has been observed that crack progression is more sensitive in comparison to crack initiation since EIRR is changing faster in crack progression and the same is also for J.P. Associates Office Intersection to Shani Temple carriageway.

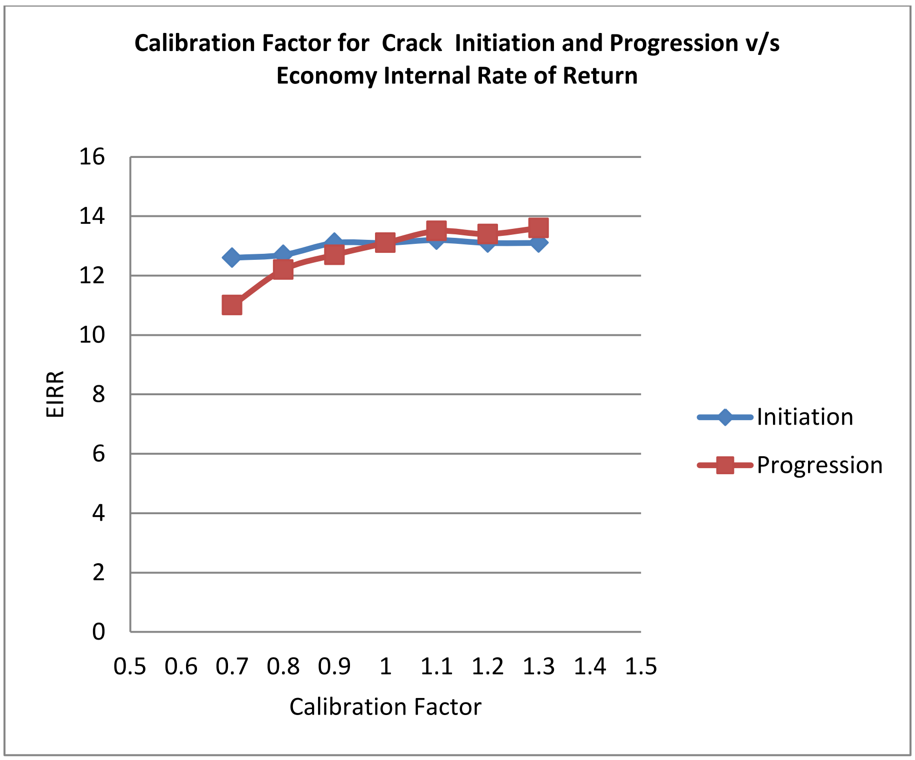


Figure 5.16: Effect of Crack Initiation and Progression with Different Calibration Factors for Shani Temple to J.P. Associates Office

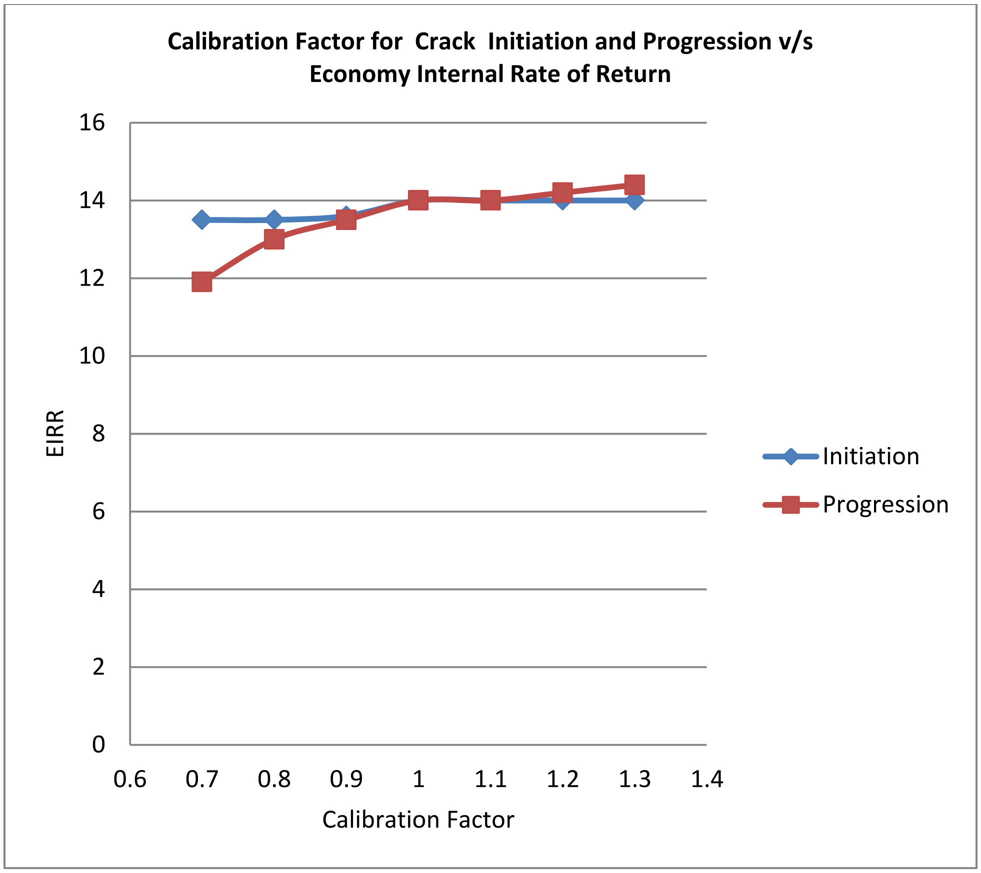


Figure 5.17: Effect of Crack Initiation and Progression with Different Calibration Factors for J.P. Associates Office to Shani Temple

5.5.1 Effect on Total Transportation Cost with Respect to Change in Calibration Factor for Crack Initiation and Progression

The Total Transportation Cost (TTC) in million Rupees increases with increase in calibration factor in cracking initiation starting from 0.7 to 1.3 whereas it is opposite for crack progression which decreases with increase in calibration factor upto default value 1 and later it increases marginally with increase in calibration factor. The same has been observed for both the carriageways of the study sections as given in Figure 5.13 and Figure 5.14.

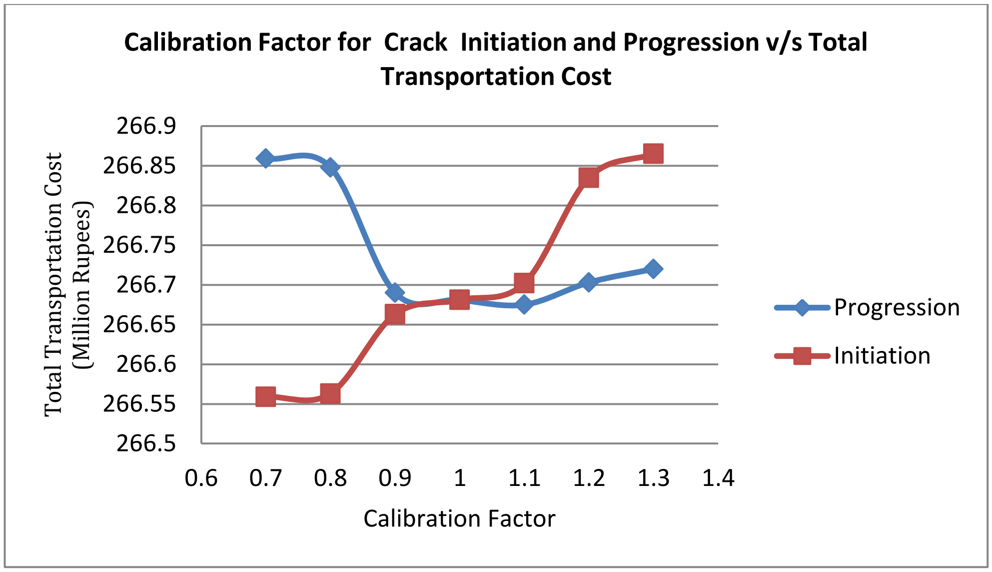


Figure 5.18: Effect on TTC for Crack Initiation and Progression with Differ Calibration Factors for Shani Temple to J.P. Associates Office

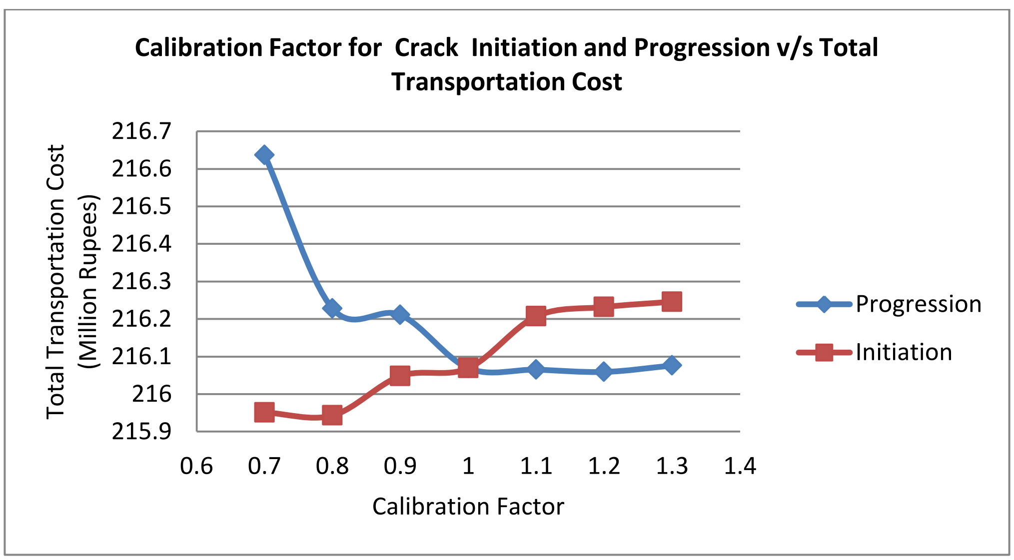


Figure 5.19: Effect on TTC for Crack Initiation and Progression with Different Calibration Factors for J.P. Associates Office to Shani Temple

5.5.2 Effect on Average Vehicle Operation Cost with Respect to Change in Calibration Factor for Crack Initiation and Progression

The average vehicle operation cost (VOC) in rupees decreases with increase in calibration factor in cracking progression.

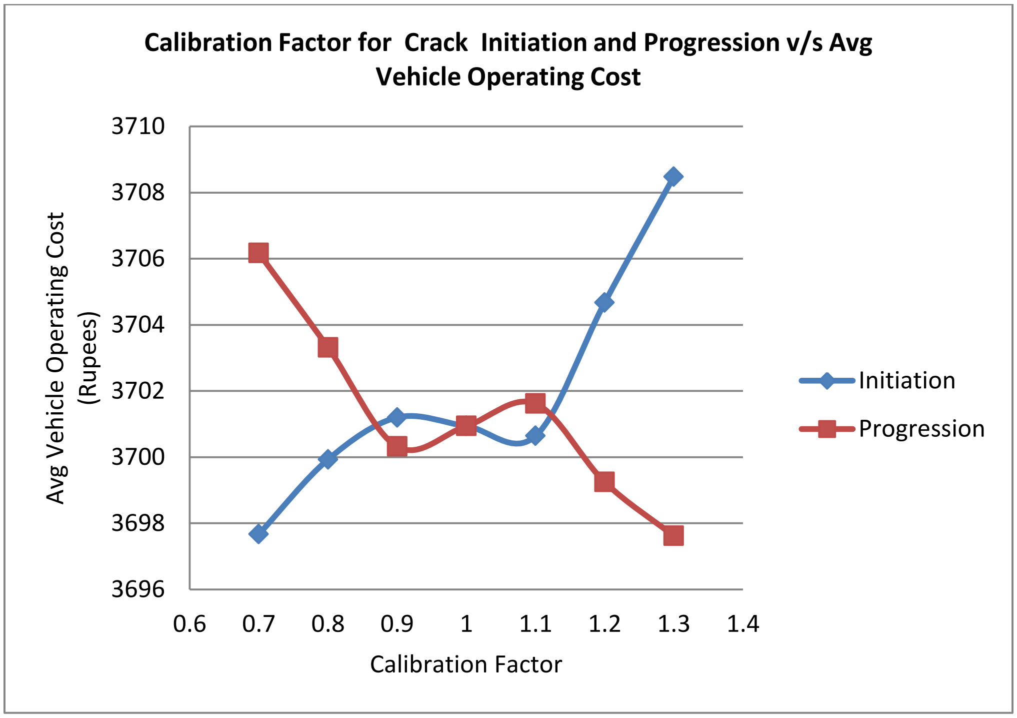


Figure 5.20: Effect on VOC for Crack Initiation and Progression with Different Calibration Factors for Shani Temple to J.P. Associates Office

The opposite has been found with crack initiation which increases with increase in calibration factor. The same has been observed for both the carriageways of the study sections as given in Figure 5.15 and Figure 5.16.

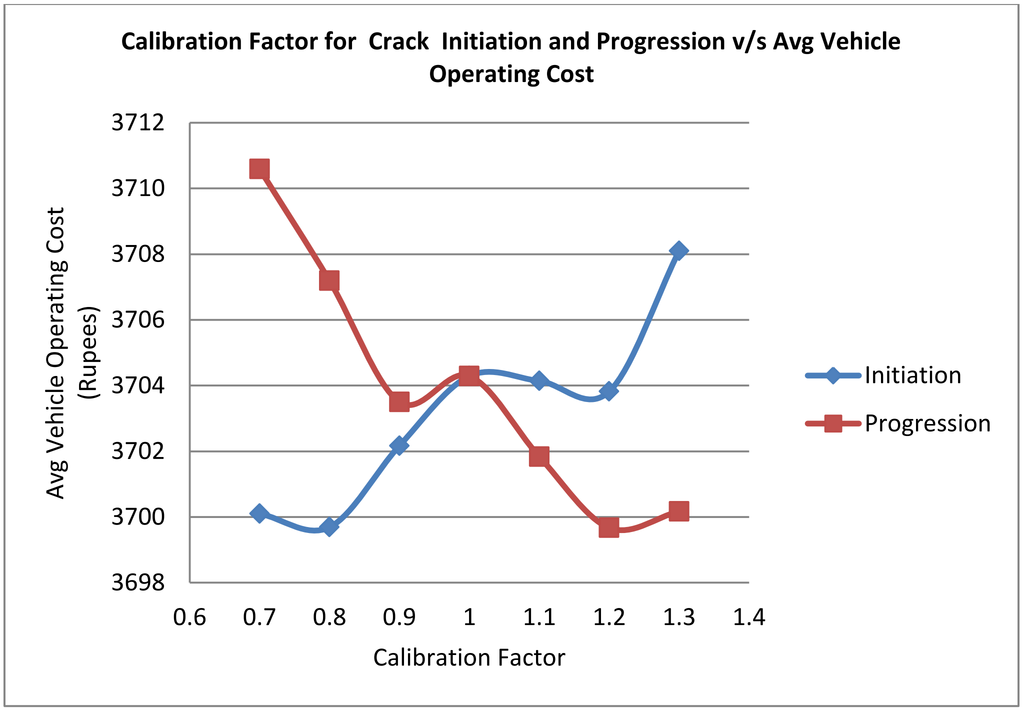


Figure 5.21: Effect on VOC for Crack Initiation and Progression with Different Calibration Factors for J.P. Associates Office to Shani Temple

5.6 Discussions

The above Figures and Tables presented in this Chapter clearly indicates the importance of calibration factors with repsect to default value of 1. The change in default value gives major impacts with respect to obtained optimized maintenance alternative. The change in year of maintenance application which is due to the effect of change in calibration factors is quite significant since the entire total construction cost for the given year changes.

CHAPTER 6

CONCLUSIONS

6.1 General

To implement a Pavement Management System (PMS) for a road network or do a project life cycle analysis it is necessary to have sufficiently accurate, reliable, consistent and timely information. Recognizing the utmost importance of quality data, it is also necessary to adapt the available models for local conditions while working on Project life cycle analysis. However, it has been found that most of the software's used for PMS / Project analysis is directly applied for a local area without calibrating for local conditions.

6.2 Effect of HDM-4 Calibrated Model

HDM-4 also have inbuilt and generic pavement distress deterioration models which can fit for any road network of an area irrespective of climate and environmental conditions. This may give outputs but may not be realistic and adaptable. Therefore in the present thesis an attempt has been made to do life cycle analysis for a live project by giving inputs obtained directly from field surveys. The impact of non-calibrated and calibrated distress deterioration models has been found herein and the importance of calibrated models has been presented. The following conclusions have been drawn which are as follows:

1. HDM-4 software was used for Life cycle analysis using data from a live project where five maintenance alternatives (standards) were formulated in HDM-4 software.
2. Based on economic indicators (in comparison to base alternative), maintenance Alternative 1 (Surfacing by 25 mm SDBC) has been identified as the optimized maintenance standard for life cycle analysis in 20 years of design life.
3. Intervention criteria of cracking >=15 % of total area has been kept for all five maintenance alternatives, so that effect of varying calibration factor can be found.

4. All the road distress deterioration viz. total cracking area and mean rut depth with roughness progression are arrested within the defined constant intervention criteria for all maintenance alternatives which is cracking >=15 % of total area.
5. It has being observed (Table 5.3) that increases in calibration factors from 0.7 to 1.3, the maintenance alternative intervenes early viz. one year before viz. maintenance alternative 1 is triggered in the year 2022 for calibration factor 1.3 and triggered in the year 2024 for calibration factor 0.7.
6. EIRR is quite sensitive for crack progression in comparison to crack initiation (Figure 5.11 and Figure 5.12).
7. Total Transportation Cost (TTC) increases with increase in calibration factor for cracking initiation ranging 0.7 to 1.3 (Figure 5.13).
8. TTC has been found opposite for crack progression which decreases with increase in calibration factor which later on increases marginally with increase in calibration factor from default value of 1 (Figure 3.14).
9. The average vehicle operation cost (VOC) decreases with increase in calibration factor in cracking progression (Figure 5.15).
10. The average VOC with respect to crack initiation increases with increase in calibration factor (Figure 5.16).

From the above inferences it has been found that the impact on economic cost is quite significant with varying calibration factor and ensures the quality data should be used with calibration of models in comparison to non-calibrated models.

6.3 Limitations of the Study

The following are the limitation of the study:

1. The project length for life cycle analysis is quite less which is only 1.4 km for one directional carriageway.
2. The number of motorized and non-motorized vehicle are basically quite less in comparison to three lane one directional traffic which is due to new construction (5 to 6 years old) and not directly connected to arterial road though itself being a connection to arterial road.
3. Overloading factor is quite less and not pre-dominant since number of commercial vehicles is quite less.
4. Since vehicles are less therefore roughness condition is satisfactory.
5. Only cracking has been found on both the carriageway therefore effect of varying calibration factor has been undertaken only for crack initiation and progression.

6.4 Future Scope of Research

1. The same attempt should be made for a large road network in comparison to the present study consisting of only 1.4 km.
2. Best calibration factor for a particular condition will be achieved by performing the above

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SHANI TEMPLE TO J.P. ASSOCIATE OFFICE

Dial Gauge Reading	Particulars	Test Point No.																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Initial	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Av.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Intermediate	1	58	82	64	63	62	51	70	85	70	67	64	61	71	67	70	72	87	88	77	70	72
	2	58	84	63	65	63	50	72	83	69	68	65	60	72	70	67	73	85	85	79	72	74
	3	56	83	64	64	64	52	70	86	70	66	66	63	70	68	69	73	81	84	81	72	74
	Av.	57.3	83.0	63.7	64.0	63.0	51.0	70.7	84.7	69.7	67.0	65.0	61.3	71.0	68.3	68.7	72.7	84.3	85.7	79.0	71.3	73.3
Final	1	59	84	65	65	63	53	72	87	71	69	65	63	72	69	71	73	89	89	79	72	74
	2	60	86	64	67	64	52	73	85	70	70	67	62	74	71	69	75	86	87	81	73	76
	3	58	84	66	66	66	53	72	87	72	68	68	64	72	70	70	74	82	86	82	74	75
	Av.	59.0	84.7	65.0	66.0	64.3	52.7	72.3	86.3	71.0	69.0	66.7	63.0	72.7	70.0	70.0	74.0	85.7	87.3	80.7	73.0	75.0
Rebound Deflection(mm)		1.18	1.69	1.30	1.32	1.29	1.05	1.45	1.73	1.42	1.38	1.33	1.26	1.45	1.40	1.40	1.48	1.71	1.75	1.61	1.46	1.50
Deflection after Temp. Correction (mm)		1.07	1.58	1.19	1.21	1.18	0.94	1.34	1.62	1.31	1.27	1.22	1.15	1.34	1.29	1.29	1.37	1.60	1.64	1.50	1.35	1.39
Seasonal Correction Factor		1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10	1.10
Corrected Rebound Deflection(mm)		1.18	1.74	1.31	1.33	1.29	1.04	1.47	1.78	1.44	1.40	1.35	1.27	1.48	1.42	1.42	1.51	1.76	1.80	1.65	1.49	1.53
Standard Deviation (σ), mm		0.20																				
Characteristics Deflection		**1.86**																				

J.P. ASSOCIATETO SHANI TEMPLE

Dial Gauge Reading	Particulars	Test Point No.																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Initial	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Av.	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Intermediate	1	61	67	74	75	92	85	83	81	65	82	83	82	81	72	61	70	87	87	82	79	72
	2	53	67	75	72	93	84	82	84	68	78	75	81	82	65	68	73	85	88	82	78	73
	3	55	68	76	71	92	85	83	83	69	77	76	79	83	66	66	72	82	87	85	80	66
	Av.	56.3	67.3	75.0	72.7	92.3	84.7	82.7	82.7	67.3	79.0	78.0	80.7	82.0	67.7	65.0	71.7	84.7	87.3	83.0	79.0	70.3
Final	1	62	69	76	76	94	86	85	82	67	84	85	84	82	74	62	72	89	88	84	81	73
	2	55	68	76	73	93	86	84	85	70	79	77	82	83	66	70	74	87	89	84	79	74
	3	57	69	78	73	94	86	85	85	71	78	78	81	85	67	67	72	85	89	87	82	68
	Av.	58.0	68.7	76.7	74.0	93.7	86.0	84.7	84.0	69.3	80.3	80.0	82.3	83.3	69.0	66.3	72.7	87.0	88.7	85.0	80.7	71.7
Rebound Deflection(mm)		1.16	1.37	1.53	1.48	1.87	1.72	1.69	1.68	1.39	1.61	1.60	1.65	1.67	1.38	1.33	1.45	1.74	1.77	1.70	1.61	1.43
Deflection after Temp. Correction (mm)		1.16	1.37	1.53	1.48	1.87	1.72	1.69	1.68	1.39	1.61	1.60	1.65	1.67	1.38	1.33	1.45	1.74	1.77	1.70	1.61	1.43
Seasonal Correction Factor		1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01	1.01
Corrected Rebound Deflection(mm)		1.17	1.39	1.55	1.49	1.89	1.74	1.71	1.70	1.40	1.62	1.62	1.66	1.68	1.39	1.34	1.47	1.76	1.79	1.72	1.63	1.45
Standard Deviation (σ), mm		0.18																				