

**DEVELOPMENT AND COMPARATIVE STUDY OF THE
VARIOUS PAVEMENT DETERIORATION PREDICTION
MODELS FOR URBAN ROADS**

A thesis submitted in partial fulfilment of the requirement for the degree of

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IN

INFRASTRUCTURE ENGINEERING

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DECLARATION

I hereby declare that this work which is being presented in the thesis entitled "Development and Comparative Study of the Various Pavement Deterioration Prediction Models for Urban Roads" in partial fulfilment of the requirement for the award of degree of Master of Engineering in the field of Civil Engineering with specialization in Infrastructure Engineering submitted at Thapar Institute of Engineering & Technology (Patiala) is an authentic record of my own work carried out during the period from 14.8.2018 to 31.7.2019 under the guidance of Dr. Tanuj Chopra for his timely and guidance and support.

The matter embodied in this thesis has not submitted by me for the award of any other degree or diploma.

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An efficacious project can on no occasion be prepared by the single effort or the person to whom project is assigned, but it also demands the help and guardianship of some conversant person who helps in the undersigned actively or passively in the completion.

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Neeraj Sharma

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LIST OF ABBREVIATIONS

VOC	VEHICLE OPERATING COST
LOS	LEVEL OF SERVICE
GP	GENETIC PROGRAMMING
NH	NATIONAL HIGHWAY
SH	STATE HIGHWAY
MDR	MAJOR DISTRICT ROAD
UR	URBAN ROADS
RR	RURAL ROADS
HDM	HIGHWAY DEVELOPMENT MANAGEMENT
LCA	LIFE CYCLE ANALYSIS
DFT	DEPARTMENT OF TRANSPORT
RUC	ROAD USER COST
RSL	REMAINING SERVICE LIFE

ABSTRACT

The road transportation is in great demand due to some of its features and advantages. Indian road network is the second largest network in the world, majorly consisting of NHs, SHs, MDRs, UR and RR. The maintenance of road networks at present is very essential because of the fact that if a road is not maintained properly this may lead to a very high rehabilitation cost. To save the cost of transportation there is very heavy loading in the vehicles that exceed as much as double the required standards. Almost more than half of Indian roads are in bad conditions.

The focus of this study is to predict the future state of roads by predicting the distresses of the pavements that is a measure to know the pavement current condition. The study uses the models with the available survey data of road pavements and traffic. The HDM-IV, GP and CRRRI models have been taken for the study. The remaining service life of pavements has been predicted as per the intervention criteria used. The preferences of roads that will need immediate actions can be known from the RSL.

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CHAPTER-1

INTRODUCTION

1.1 GENERAL

Today India is considered among the top fastest developing countries. It's been said that a good transportation network has to be there for a country's good economy and in India, roadway network has been the back bone of the transport network. Although, road transport has been the major means of transportation in India from a long time due to its geographical and other factors.

In the past, India had not invested enough resources in building and maintaining its road network. But this has changed from early 90's, there has been put so much of efforts in developing modern, safer and economical road infrastructure. This development has taken a pace since 2014, due to the honourable Mr. Nitin Gadkari's great effort in road infrastructure. Indian road network has been spread over almost 59 lakh km, making it 2nd largest in the world.

Indian Road network is enormous, but the condition of these roadways is not good. Since these roads are indirectly responsible for the economic growth of the country, it is necessary that roadways are nicely laid. These roadways conditions issues are not new and these issues has been dealt with since a long time. Indian roads have been facing problems like bad rider quality, insufficient pavement thickness and poor geometrics.

Improper and untimely maintenance results in considerable deterioration of roadways resulting into high VOC, large number of accidents and reduced LOS. If the maintenance work cannot be delayed any further, it'll result in extensive rehab. Or even reconstruction, this leads to cost going many a times than the cost of maintenance treatment. Untimely and inadequate maintenance result in increased ultimate repair cost, road-user costs and inconvenient road-use and reduced road safety. So, it is important to carry out road maintenance on time.

The main aim of the highway and pavement engineers should be to make sure a healthy pavement quality index both in terms of structural as well as functional keeping an eye on several aspects such as economical, safety and environmental. But it is not an easy task to develop and maintain a good road network. It requires a great and careful attention in planning, enormous funding, demanding construction techniques, meticulous quality check and other related respects. Now is the time when roads has to be managed and not just maintained.

The Highway Development and Management Model popularly known as HDM-IV is a toolkit that has been developed by the World Bank. It's been developed for checking and performing technical and economic assessment of the road projects throughout the world. HDM-IV is a predictive model that has been developed to model the road deterioration by interrelating the vehicle characteristics, pavement characteristics (surface and structure) and the environmental conditions. The predictions of various pavement distresses are done by deterioration models over time that is to be specified and under traffic that is to be input and the yearly growth, traffic pattern and composition has also to be specified.

GP is based upon the Genetic algorithms that John R.Koza proposed in the year 1992. genetic programming (GP) is a process of evolving programs, starting from a sample of some unfit (usually random) programs, developed for a particular operation by applying by pass to natural genetic processes to the sample of programs. This program searches for an optimum or close to optimal program among the group of all programs. Sometimes, particular run of the algorithm gives results that are not globally optimal or even good solution. A very good result is produced by running GP for multiple times may be dozens or hundreds. Sometimes starting population size has to be increased and variability of the individuals to avoid bad results.

1.2 RAOD NETWORK IN INDIA

It has been seven decades since India's Independence and the road network in India has been diversely developed with regard to length as well as density. The expansion of the Indian roads has been increasing day by day. Indian road network consists of

Expressways, NH, SH, MDR, VR and UR. The length of the roads over the time is given in Table 1.1 [MORT&H, 2017].

Table 1.1 Length of Different Indian Roads Over the time

Period	NHs	SHs	District Roads	Rural Roads	Urban Roads	Project Roads	Total
1950-51	19811	-	173723	206408	-	-	399942
1960-61	23798	-	257125	197194	46361	-	524478
1970-71	23838	56765	276833	354530	72120	130893	914979
1980-81	31671	94359	421895	628865	123120	185511	1485421
1990-91	33650	127311	509435	1260430	186799	209737	2327362
2000-01	57737	132100	736001	1972016	252001	223665	3373520
2010-11	70934	163898	998895	2749804	411679	281628	4676838
2013-14	91287	170818	1082267	3304328	457467	296319	5402486
2014-15	97991	167109	1101178	3337255	467106	301505	5472144
2015-16	101011	176166	561940	3935337	509730	319109	5603293
2016-17	114158	175036	586181	4166916	526483	328897	5897671

Source: MORT&H (2016-17)

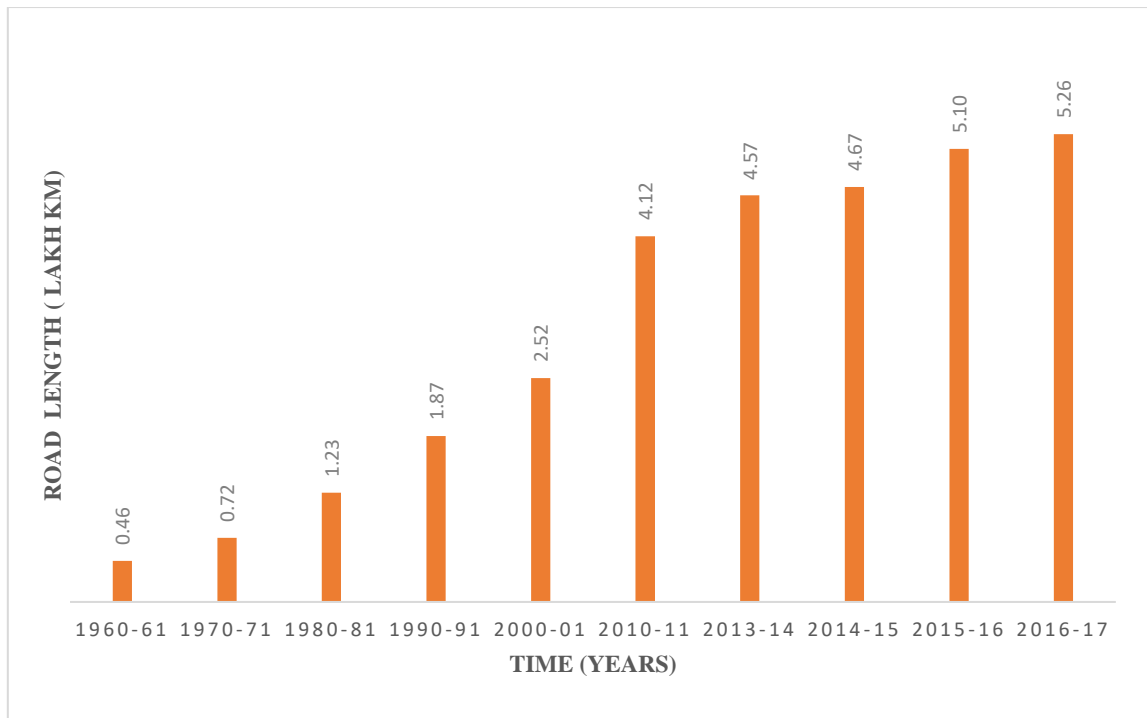


Figure 1.1 Growth trend of Urban Roads in India

Source: MORT&H (2016-17)

1.3 URBAN ROADS

Urban roads are planned as an interconnecting road network to connect user of various resources. There is very limited maintenance in urban roads but the flow of traffic is very large and continuous. So different provisions have been added in Indian Standards of practises for the urban roads. The main function of the urban road(arterial) is to deliver traffic from collector street to main ways, facilitating communication between various centres of cities/towns. Various public utilities are also dependent on these roads like water mains, drainage pipes etc.

Urban roads can be classified in following categories

- Expressways
- Arterial Roads
- Sub-Arterial Roads
- Collector Streets
- Local Streets

Table 1.2 Total & Surfaced Length of Urban Roads

Sr. No.	State/UT	Total	Surfaced
1	Andhra Pradesh	24424	19767
2	Arunachal Pradesh	576	464
3	Assam	6319	4056
4	Bihar	8891	3801
5	Chhattisgarh	12834	10997
6	Goa	870	775
7	Gujarat	28816	23506
8	Haryana	15042	10961
9	Himachal Pradesh	3489	2922
10	Jammu & Kashmir	1757	1744
11	Jharkhand	6799	4642
12	Karnataka	51334	35629
13	Kerala	33201	26255
14	Madhya Pradesh	17305	13569
15	Maharashtra	24245	19273
16	Manipur	151	96
17	Meghalaya	170	166
18	Mizoram	312	265
19	Nagaland	100	98
20	Odisha	20893	15849
21	Punjab	17868	16163
22	Rajasthan	30214	25668
23	Sikkim	48	46
24	Tamil Nadu	24494	22783
25	Telangana	12058	8237
26	Tripura	602	445
27	Uttarakhand	5446	3806
28	Uttar Pradesh	63722	48741
29	West Bengal	95240	66950
30	A & N Islands	170	153
31	Chandigarh	2523	2523
32	Dadra & Nagar Haveli	83	83
33	Daman & Diu	147	147
34	Delhi	15299	15299
35	Lakshadweep	2	2
36	Puducherry	1038	987
Total		526482	406868

Source: MORT&H (2016-17)

Expressways are built for moving large volume of motor traffic at very high speed. Pedestrians are not allowed in such roads. The traffic moving in different/opposite sides of the road are separated by a divider or median. There are minimum/zero curves, steep gradients are avoided and level crossing are not avoided.

Arterial Roads are the ones which carry great masses of traffic inside the city and join CBD (Central Business District) with outside residential areas of the city/town. Ring roads, by-passes are type of arterial roads. Only at intersections, the pedestrians have access to cross the road. Arterial roads are not allowed through residential areas.

Sub Arterial roads are contained within city limits and they connect important city/town centres. The traffic over short distances moving slowly are served by these roads. Restricted and controlled parking, loading and unloading is there.

Collector Streets collect traffic from different parts of the city/town and carry it to other major or minor roads. These roads provide access to adjoining properties and the non-vehicular traffic is given importance. Local road network is not allowed to come in contact with arterial roads and are separated by a bridge most of the time.

1.4 CONDITION SCENARIO OF INDIAN ROADS

It has become an enormous task for road engineers to construct and maintain the roads, with the ever growth of road transportation. The current roadway network has fallen greatly short both of the requisite capacity and adequacy. There is occurring a higher cost of transportation because of overstraining of the existing roads and the vehicle fleet because of the increased demands. With regard to geometrics, design and standards, most of the roads have shortcoming in them. So, these reasons reflect in large number of accidents, traffic congestion, delays resulting into increased VOC.

The huge investment has been done in establishing the network but there is a serious concern of rapid deterioration of these roads. Higher traffic and higher vehicle fleet loads than the specified as per standards of practises are one of the reasons for this accelerated deterioration. Other main reason is the shortfall in the funds that has to be provided by public authority to construct and maintain the roads. Due to the absence of

timely maintenance because of many reasons, there is a huge loss in terms of VOC and future rehabilitations.

1.5 INADEQUACIES AND DEFICIENCIES OF URBAN ROADS

There are many inadequacies and deficiencies in the current road network. Some of these are:

1.5.1 GROWING ROAD TRANSPORTATION DEMAND

The post-independence era has seen enormous road traffic growth. The goods being carried through road transportation has seen a tremendous rise. The share of road transportation in passenger mobility and freight mobility has gone to 85 percent and 70 percent over the last 66 years. When there is a comparison between the two main modes of mobility i.e. road transportation and railways, it can be observed that a considerable shift is there in traffic that has been carried by road transportation as compared to rail transportation over the last 65 years, as given in Table 1.2 [MORT&H].

Table 1.3 Modal Shift in Traffic Categories

Traffic Category	Year 1951		Year 2013	
	Rail	Road	Rail	Road
Passenger	80%	20%	15%	85%
Freight	80%	20%	30%	70%

Source: NHAI

1.5.2 LOWER QUALITY OF ROADS

The roads of Indian road network are not of good quality, more than half of roads in country are still without any type of paving. The existing road has become old and has aged, leading to various distresses like cracking, potholing and ravelling on the surface. Because of the action of moving traffic and environment factors, these pavement distresses have been continuously growing without the timely maintenance. There is a

very bitter fact about the Indian road network that the back bone the network i.e. NHs, 85% of the NHs are not structurally adequate to even carry the standard axle of 10.2 tonnes.

1.5.3 INCREASED TRAFFIC AND AXLE LOADS

The volume and axle load of the Indian road traffic has been growing at an alarming rate, the annual rate of growth is around 10 percent as per [MORT&H 2001c]. A tremendous effect has been put on the roads due to these excessive strains. The load carried by freight vehicles has been increasing considerably, but the standard permissible axle loads has not been changed by the governing body. The present Indian road's axle loads spectrums have shown that commercial vehicles are not plying on legal axle load of 10.2 tonnes, instead the commercial vehicles has been observed to carry axle loads to extent of 20-22 tonnes. The pavement that has 10 years of service life will only last until 6.5 years according to 'Road Damage Formula' with average 10 percent overloading. This road will withstand only 3.5 years if the overloading is 30 percent [CRRI 1994]. This demands additional maintenance inputs at time, to make sure the minimum acceptable LOR.

1.6 NEED OF PMMS OF THE ROADS

It is very important that there is timely maintenance of the road network since a large amount of money and resources is invested in developing the road network. In a developing country like India there is shortage of the assets required to the assets needed most of the time specially in urban roads.

Currently, In India, the subjective judgement and engineering work experience is used to decide and provide the maintenance and Rehabilitation strategies. The pavement evaluation and analytical tools are not used to find out the maintenance and rehabilitation strategies. Instead basic overlay or patching is done when the road deteriorates drastically.

Characterization of the pavement is of clutch importance in allocating the resources required for the rehabilitation of the rapidly deteriorating road. Currently,

visual inspection and empirical procedures are predominant. There is a visible attraction towards more rational methods of pavement assessment. There are few mechanical and AI based devices which are available to engineers for this purpose.

The pavement evaluation of the road pavement is done and existing road conditions are determined in terms of surface unevenness and structural adequacy. The obtained data from the pavement evaluation is used to decide which type of maintenance strategy is required.

The PMMS of the roads is needed to make sure following:

- Road system meet the traffic demands
- Proper Planning
- Proper Construction and Management of resources
- Pavements don't fail pre maturely

A PMMS is a defined set of procedures for gathering, analysing, maintaining and reporting the pavement data, to make planners find and decide the best possible strategies for maintaining the pavement in desirable LOS. PMMS is developed so that road managers can make timely decisions on pavement preservation that are more consistent and economic.

1.7 OBJECTIVES OF THE STUDY

The major objective of the research study is to compare the different pavement deterioration prediction models developed through various software's and researchers. The objectives of the study are:

- Prediction of Pavement Distresses in Pavement using HDM-IV
- Determining the Remaining Service Life of the Pavements
- Suggesting Pavement Rehabilitation and Maintenance Strategy as per Pavement Distresses
- Prediction of Pavement Distresses using CRRM Model
- Prediction of Pavement Distresses using GP Model

- Validation of GP Model
- Comparison between Different Models of Pavement Distresses

1.8 THESIS OUTLINE

Acknowledging the above parameters, the thesis was entitled “**Comparative Study of the Various Pavement Deterioration Prediction Models for Urban Roads**”, which deals with the analysis the different pavement deterioration models. The models have been used in the study are:

1. HDM-IV Model
2. GP Model
3. CRRI Model

All the three models have been discussed and the analysis has been done there after. A proper comparison based upon their predicted distresses has been done.

The thesis comprises of six chapters:

- ❖ **First** chapter contains the general introduction to the study, defines the problems and presents its way to rectify them.
- ❖ **Second** chapter describes about the PMMS using HDM 4.
- ❖ **Third** chapter contains the past studies that has been done in past.
- ❖ **Fourth** chapter deals with PMMS development using HDM 4 and its various steps and M&R strategy
- ❖ **Fifth** chapter contains the pavement distress predictions done with GP and CRRI model
- ❖ **Sixth** chapter contains results and the conclusions.

CHAPTER-2

PAVEMENT MAINTENANCE MANAGEMENT SYSTEM AND HDM 4 MODEL

2.1 INTRODUCTION TO PMMS

To manage or direct and control the pavement maintenance recourses, for the optimum benefits, in a scientific way, a methodology is required which is technically or operationally sound, Pavement Maintenance Management System PMMS is one such methodology. PMMS has become very important as it has been observed that the pavement M&R strategies reduces the cost up to half of the reconstruction. PMMS is a system that looks after the road condition analytically and lets road agencies know when where and which M&R strategies are to be implemented. The one of the major objectives of the PMMS is to assist pavement engineer to make economic and consistent decision relating to the construction, maintenance and rehabilitations of pavements [MORT&H Guidelines of Urban Road,2004]. PMMS performs the following functions:

- Identification of the pavements that require M&R
- Establishment of Priorities
- Identifying the type of Maintenance & Rehabilitation required and best suited.
- Predicting the time and type of future Maintenance & Rehabilitation
- Ensuring Maximum benefit and minimum Cost
- Prediction of future performance of pavements

2.2 COMPONENTS OF PMMS

Database: Road inventory, history data, pavement conditions data and traffic data are included in PMMS database.

Pavement Analysis Program (P.A.P.): PAP is a set of tools which computes the pavement conditions and decides which maintenance strategy to be implemented based upon conditions and other criterions. Annual work program and the amount of budget

needed are also decided by these tools. There are some useful reports that are generated through this tool.

2.3 PMMS BENEFITS

- It Provides inventory of pavements which includes type of pavement, functional classification, pavement area etc.
- Defines an estimated budget required to bring road sections to desired condition from the current condition.
- The current condition of the road networks is shown for obtaining information of the pavement conditions.
- It is a base for comparison of Maintenance & Rehabilitation steps of the road network.
- It produces a list of Maintenance & Rehabilitation steps which can be reviewed by the agency for choice of final project
- It acts as a base for communicating between groups outside an agency i.e. public governing bodies, city councils, media etc.

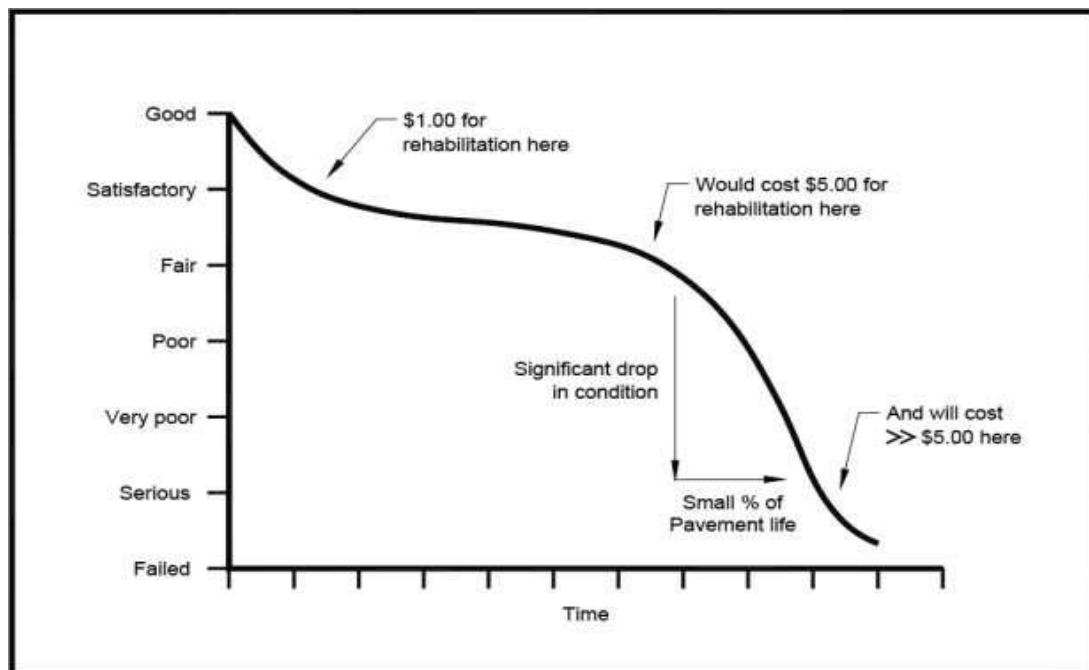


Figure 2.1 Typical Road Deterioration with Time

In Figure 2.1, it is shown that how important is the development of the PMMS for a road network. With the aging or continuous traffic loading the existing pavement deteriorates. In figure, there are three trigger points for showing the M & R. If the treatment is triggered at first point then the cost will be minimum, similarly, if the rehabilitation is done at second trigger point then this will cost much more than rehabilitation done at first trigger point. Similarly, if the M&R strategy is triggered at third point then the cost will be very-2 large and there are chances that pavement might not be recovered completely and some very costly steps need to be taken.

2.4 BACKGROUND OF HDM-4 MODEL

- In the year, 1968, the World Bank took a step towards developing a project appraisal model for roads i.e. Highway Cost Model (HCM).
- In the year 1976, To further develop the HCM, more funding was given by world bank and that resulted the 1st version of Highways Design&Maintenance (HDM).
- In the year 1987, A more eclectic model was developed integrating the finding from the previous studies and it gave HDM- III.
- By the year 1995, this model was almost 10 years old. So, it was decided to integrate the result data of the immense probing that had been going throughout the world throughout this period. Since the year 1980 there has been dramatic change in the VOC and this is due to the improvement in vehicle technology. This has resulted way less than operating cost of the vehicle predicted by the HDM-III.
- It became very crucial to upgrade this model. There was need of addition in capabilities such as model for traffic congestions, various climatic effects, various types of pavements and its structures, road safety, environment effect.

HDM-IV was brought to India by the studies of Central Road Research Institute (CRRI). The CRRI had carried a very huge research regarding the different pavement and road characteristics as well as environmental and other features responsible for pavement deterioration directly or in indirectly.

2.5 ROLE OF HDM-IV IN HIGHWAY MANAGEMENT

HDM-4 model has various roles in highway management in the form of following highway management functions:

Planning

Planning 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. The physical highway section system is usually characterized at the planning stage by:

- (i) Characteristics of the road network
- (ii) Length of road in each category
- (iii) Characteristics of vehicle fleet which use the road network

Programming

Programming involves the programme or 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. 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 for each road section. Budgets are typically constrained, and a key aspect of programming is to prioritize the road works in order to find the best use of the constrained budget.

Preparation

This is short-term planning stage Where road schemes are packaged for implementation. At this stage, designs are prepared in more details: bills of quantities and detailed costing are prepared together with work instructions and contracts.

Detailed specifications and costing are likely to be drawn up, and any cost-benefit analysis may be revised to confirm the feasibility of the final scheme. Works on adjacent road sections may be combined into a package of a size that is cost-effective for work execution. Typical preparation activities are the detailed design of following: an overlay scheme and Road Improvements works.

Operation

Operation activities cover the on-going operation of an organization. Decisions about the management of operations are made typically on a daily or weekly basis including the schedule of work to be carried out and monitoring in terms of supervisor and labour. Activities are normally focused on individual sections or subsections of a road, its measurements often being made at a relatively detailed level.

2.6 ANALYTICAL FRAMEWORK OF HDM-IV

The HDM-IV analysis framework is based upon the concept of LCA of the pavements. These are applied for the prediction of the following parameters throughout the pavement life cycle, typically is 15 to 40 years [Kerali, 2000].

- a) Road Deterioration (RD)
- b) Road Work Effects (RWE)
- c) Road User Effects (RUE)
- d) Socio-Economic and environmental Effects (SEE)

After the construction, the road pavements start deteriorating as repercussion of number of factors, notably traffic loading, improper drainage system and environmental weathering.

The assigned maintenance or improvement standards are directly responsible over all long-term condition of the pavement. In figure 2.2, it has been shown that predicted trend of performance of pavement is illustrated by the ridership quality which has been mostly measured in IRI units i.e. International Roughness Index [Kerali 2000]. A limit

is imposed on the maintenance standards while defining it on the permitted limits of pavement deteriorations.

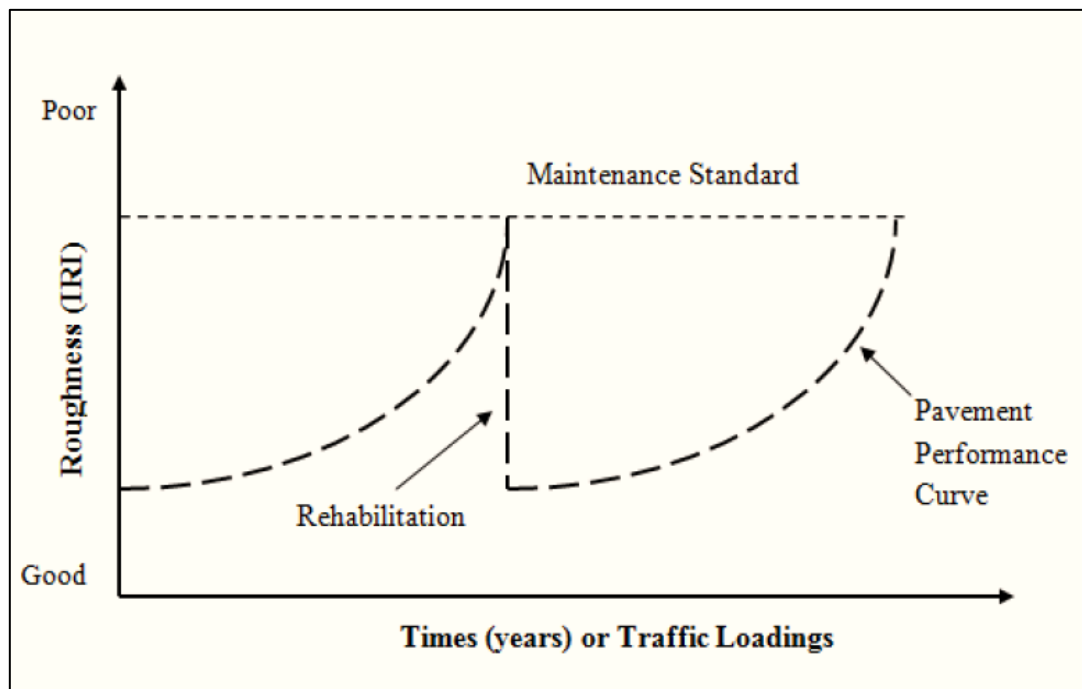


Figure 2.2 Concept of Life Cycle Analysis (LCA) in HDM-IV

Road User Costs is the term used to measure the impact of pavement condition as well as the pavement design standards. VOC, Cost to economy and Costs of Travel Time make up the Road user costs combining. In HDM-IV, Road User Effects are calculated by the prediction of physical quantities of resource consumption.

2.7 HDM-IV INPUT DATA MODLUES

Three analysis tools i.e. Strategy, Program and Project operate on the data defined in one of the following four data managers:

- a) HDM-IV configuration
- b) Road network
- c) Vehicle fleet
- d) Work standards

HDM-IV Configuration: HDM-IV configuration comprise of traffic flow patterns, speed flow patterns, speed flow patterns, climatic zone, currency and aggregate data and tables. HDM-IV has valued stored in its system, but these all values can be changed by user as per the work study environment.

Road Networks: In this section, the basic facility to store the characteristics of road sections is provided. It gives user a freedom to set different networks, sub-networks and most importantly, the fundamental unit of analysis i.e. road sections. There different data entities that are supported inside the road network embody section names, section ID, lengths, carriage widths, shoulder widths, traffic in AADT, speed and traffic patterns, climatic zone, pavement surface class, rise and fall in gradient, speed limits, average horizontal curvatures, altitude and drainage type, surface type, pavement thickness, past work-done on pavement and adjusted structural number (SNP), year-end condition of road, roughness (IRI), total cracking areas, ravelled areas, pothole count, mean rutting depth, drainage etc. Calibration factors for distresses can be assigned corresponding to work study environment.

Vehicle Fleet: Vehicle Fleet offer means of storing and retrieving vehicular characteristics needed to calculate the vehicle speeds, operational costs, travel time costs and other vehicle effects. Motorised and Non-Motorised vehicles are enclosed with their primary characteristics and financial unit costs. Multi vehicle fleets datasets may be established to be used in numerous analysis, with a large domain of available base data.

Work Standards: Road work standard refers to the target or level of conditions and responses which the management organizations target to reach. Road organization establish different benchmarks which are to be applied in on-field situations, so as to satisfy the precise objective that are associated with basic attribute of road networks structure. The work standards wallet contains provision inside a versatile structure to outline the inventory of maintenance standards and rehabilitation standards with their default work costs that are followed by road organizations in the network management and network development.

2.8 HDM-IV APPLICATIONS

Strategy Analysis: It handles all the networks or sub-networks that a road organisation manages. HDM apply the main features that interfere in pavement performances and road user costs which are defined by a road network matrix for the prediction of needs of complete road sub-network or network. A basic road network matrix might be classified in line with the following: traffic volume or loading, pavement types, pavement conditions, atmosphere or environmental condition zones, functional classification [Kerali et al., 2000]

Program Analysis: This deals basically with the prioritizing a outlined long list of the discrete segments of a road network into single-year or multiple-year works program under defined budget constraints. The program analysis may be used to collate the life cycle costs foreseen beneath the present plan of pavement management against the life cycle costs forecasted for the scheduled maintenance, road development and enhancement alternatives.

The main distinction between strategy and program analysis is the way of physical identification of links and sections of a road. Program analysis handles individual links and sections that acts distinctive physical units throughout analysis. The road system primarily loses its unique link and section characteristics in strategy analysis by assembling all road segments with similar attributes into the road network matrix classes. [Kerali et al., 2000].

Project Analysis: Project analysis is focused on the following; “Evaluation of one or more road projects or investment options. The application analyses a road link or section with user-selected treatments, with associated costs and benefits, projects annually over the analysis period. Economic indicators are determined for different investment options.” Project analysis can be used to predict the economical or engineering viability of road projects by the consideration of problems such as structural performances of pavement, life cycle deterioration predictions, road works effects and costs, road user costs and economic comparisons of project alternatives [Kerali et al., 2000].

2.9 PAVEMENT DISTRESSES AND THEIR USE IN HDM-IV MODELING

There are various distresses in the pavement which are to be input in order to develop a optimum model for the pavement maintenance management system that will predict future distresses and the strategies to deal with these distresses. The common flexible pavement distresses are:

Table 2.1 Common Flexible Pavement Distresses

Category	Type of Distress
Cracking	Fatigue Cracking, Block Cracking, Edge Cracking, Longitudinal Cracking, Transverse Cracking, Slippage Cracking.
Disintegration	Ravelling, Potholes.
Distortion	Rutting
Surface Defects	Roughness

Cracking: The cracking can be caused due to traffic loading, temperature or extreme environmental conditions. If cracks remain un attended they may lead to major pavement deterioration. The repair of the cracks depends upon the type of crack. There are several types of cracks briefed below:

- a) **Fatigue Cracking's:** These are also known as alligator cracks, due to orientation of the cracks which looks like the skin of alligator. These cracks are caused due to load relating deterioration which is a result of weakened base, sub base or sub grade, less thickness than required, overloading or a combined effect of all these factors.
- b) **Block Cracking:** It consists of large, rectangular cracks on a bituminous pavement surface. Block cracking covers very large area and it might occur in the places where vehicle movement is very less. This cracking is mostly caused due to shrinking of the bituminous pavement resulting from temperature variations.
- c) **Edge Cracking:** These are longitudinal cracks which develops within thirty or sixty centimeters of the outer edge of the pavements. Lack of support at pavement edges is the main reason of this cracking.

- d) **Longitudinal Cracking:** The longitudinal cracking occurs parallel to the middle-line of the road pavement. There are number of reasons of this cracking like poor construction of joints, shrinking of the bituminous layer, long-wise segregation due to inappropriate paving and cracks reflecting up due to an underlying layer.
- e) **Transverse Cracking:** The transverse cracking occurs almost across the middle-line of the pavement. These cracks may be formed due to shrinking of the bituminous layers. This type of cracking is not related to loading.
- f) **Slippage Cracking:** This cracking occurs due to poor-strength bituminous mixes or a weak interconnection among the pavement layers. This cracking is formed due to the tractive forces that result from turning or deceleration or stoppage of moving vehicles.

Disintegration: The breaking up of a pavement into smaller bits and then these are lost over the period and traffic. Below are mentioned disintegration distress:

- a) **Raveling:** The wearing away of the aggregates from the bituminous concrete is Raveling. This state suggest that the bitumen has hardened or the mix of below standards was used. Raveling come in the existence in the of traffic.
- b) **Pothole:** The potholes are holes which are bowl-shaped and are result of local disintegration of the surface of pavement. Pothole typically results from continuous deterioration of other types of distresses. Segregation, patches or cracking may lead ultimately to a pothole. The poor mixes and weak small portions in bases and subgrade lead to rapid pothole failure.

Distortion: In a bituminous pavement distortion are result of instability in an bituminous mix or weak base or subgrade layer. Below are distresses caused by distortion:

- a) **Rutting:** Rut is a depression (linear & on surface) in the wheel path. It can be caused due to pavement layers or subgrade being consolidated or deformed. There are other reasons also like improper thick pavement, less compaction and weak bituminous mix.

Roughness: Roughness is basically an expression to represent the pavement surface irregularities. These irregularities affect the ridership quality of vehicle. These surface undulations also affect the fuel consumption, maintenance cost etc. These all lead to high VOC. It is measured in the units of IRI i.e. International Roughness Index. IRI was developed by World bank in 1980's. Its common units are m/km or mm/m. There are various devices that can be used to measure roughness.

Table 2.2 Measurement Units of Pavement Distresses

Distress Type	Measurement Unit
Cracking	m ²
Rutting	m ²
Potholes	Number
Ravelling	m ²
Roughness	IRI or m/km or mm/m
Patching	m ²
Edge cracking	m

Source: Shahin (1982)

CHAPTER-3

LITERATURE REVIEW

3.1 STUDIES DONE IN INDIA

Jain et al. (2005) The study has been done in the northern states of India namely U.P. and Uttaranchal. Pavement deterioration models has been developed using HDM-IV model which has been calibrated to actual field conditions. This model can be used in other developing countries with similar environmental conditions, traffic flow patterns, terrain and crust composition of the pavement. The deterioration model has been developed considering 145 sections located in different areas. So, the model can be used through the India. The data has been collected over the period of 3 to 5 years. The model has been compared with the HDM-IV model. Celebration factors has been calculated after comparing the distresses that has been observed on field and the distresses has been predicted from HDM-IV.

Table 3.1 Indian model and HDM-IV deterioration model for Pavement

Serial number	Model description	Indian pavement deterioration models	HDM-4 road deterioration models
1	Cracking initiation (for AC surfacing)	$AGECRIN = 4.00 * EXP \left[-1.09 * \frac{CSALYR}{MSN^2} \right]$	$ICA = K_{cia} [CDS^2 * 4.21 * EXP \{ 0.14 * SNP - 17.1 * (YE4 / SNP^2) \}] + CRT$
2	Cracking progression (for AC surfacing)	$\frac{\Delta CR_t}{t_i} = 4.26 * \left[\frac{CSALYR}{MSN} \right]^{0.65} * SCR_t^{0.32}$	$dACA = K_{cpa} (CRP / CDS) * [(1.84 * 0.45 * \delta t_A + SCA^{0.45})^{1/0.45} - SCA]$
3	Raveling initiation (for PC surfacing)	$AGERVIN = 3.18 * AXLEYR^{-0.138} * (CQ + 1)^{-0.38}$	$IRV = K_{vr} * CDS^2 * 10 * RRF * EXP[-0.156 * YAX]$
4	Raveling progression (for PC surfacing)	$\frac{\Delta RV_t}{t_i} = 3.94 * AXLEYR^{0.32} * SRV_t^{0.46}$	$dARV = K_{vpr} (1 / RRF) (1 / CDS^2) [(0.6 + 3.0 * YAX) * 0.352 * \delta t_v + SRV^{0.35}]^{1/0.35} - SRV$
5	Potholing initiation (for PC surfacing)	$AGEPHIN = 0.21 * THBM^{0.23} * EXP[-0.18 * AXLEYR]$	$IPT = K_{pi} 2.0 * \left[\frac{(1 + 0.05 * HS)}{(1 + 1 * CDB)(1 + 0.5 * YAX)(1 + 0.01 * MMP)} \right]$
6	Potholing progression (for PC surfacing)	$\frac{\Delta PH_t}{t_i} = 1.49 * \frac{CR_t}{AXLEYR(1 + CQ)}$ $\frac{THMB * MSN + 3.60 * PH_t * AXLEYR(1 + CQ) + RV_t * AXLEYR(1 + CQ) + 3.47}{THBM * MSN}$	$= K_{pp} * ADIS_t \left[\frac{dNPT_t}{(1 + 1 * CDB)(1 + 10 * YAX)(1 + 0.005 * MMP)} \right] \frac{1}{(1 + 0.08 * HS)}$
7	Roughness progression (for AC surfacing)	$\Delta RG_t = [34856(\Delta CSAL / SNCK^5)] * EXP(m PAGE) + [7.43 \Delta CR_t] + [190.57 \Delta PH_t] + [22.34 \Delta PT_t] + [m RG_t * t_i]$	$\Delta RI = K_{gr} [134 * EXP(m K_{gm} AGE3) * (1 + SNP K_b)^{-5} YE4] + [0.0066 * \Delta ACRA] + [0.088 * \Delta RDS] + [0.00019(2 - FM) * \{((NPT_a * TLF) + (\Delta NPT * TLF / 2))^{1.5} - (NPT_a)^{1.5}\}] + [m K_{gm} RI_a]$

Table 3.2 Description of terms used in Models

Indian models	HDM-4 models
AGECRN=age of pavement at time of cracking initiation (years)	ICA=time to initiation of all structural cracks (years)
AGERVIN=age of pavement at time of raveling initiation (years)	CDS=construction defect indicator for bituminous surfacing (0.5=brittle, 1.0=optimum, 1.5=soft)
AGEPHIN=age of pavement at time of pothole initiation (years)	SNP=average annual adjusted structural number of pavement
SN=structural number of pavement	YE4=annual number of equivalent standard axles (millions/lane)
CBR=soaked subgrade strength at the time of pavement investigation	CRT=crack retardation time due to maintenance (years; default value=1.5)
MSN=modified structural number	dACA=incremental change in area of all cracking during year, in percent of total carriageway area
VDF=vehicle damage factor	CRP=retardation of cracking progression due to preventative treatment, given by $[CRP=1-0.12CRT]$
CVPD=commercial vehicles per day	SCA=Minimum $\{ACA_a, (100-ACA_a)\}$
PAGE=pavement age since last renewal/strengthening (years)	δt_a =fraction of analysis year in which all cracking progression applies
CR _i =initial cracking area (%)	ACA _a =area of all cracking at start of analysis year (percent)
RV _i =initial raveling area (%)	IRV=time to raveling initiation (years)
PH _i =initial pothole area (%)	YAX=annual number of axles of all vehicle classes in analysis year (millions/lane)
ΔCR_t =percent change in cracked area over time t in years	RRF=raveling retardation factor due to maintenance (default value=1.0)
ΔRV_t =percent change in raveled area over time t in years	dARV=change in area of raveling during analysis year (percent of total carriageway area)
ΔPH_t =percent change in pothole area over time t in years	SRV=minimum $\{ARV_a, (100-ARV_a)\}$
ΔPT_t =percent change in patched area over time t in years	δt_r =fraction of analysis year in which raveling progression applies
ΔRG_t =change in roughness over time t in years (mm/km)	ARV _a =area of raveling at start of analysis year (percent)
t_i =time interval (years)	IPT=time between initiation of wide cracking or raveling and initiation of potholing
SCR _i =minimum $\{CR_i, (100-CR_i)\}$	HS=total thickness of bituminous surfacing
SRV _i =minimum $\{RV_i, (100-RV_i)\}$	CDB=construction defect indicator for base (0=no defects, 1=some defects, 1.5=several defects)
CSALYR=cumulative standard axles per year (msa)	MMP=mean monthly precipitation (mm/month; average value=80)
AXLEYR=number of vehicle axles per year (millions)	dNPT _i =additional number of potholes per kilometer derived from distress type i
THBM=thickness of bituminous layer (mm)	TLF=time lapse factor depending upon frequency of pothole patching (default value=1.0)
CQ=construction quality (0=good, 1=poor)	ADIS _o =percent area of wide cracking at start of analysis year, or percent area of raveling at start of analysis year, or number of existing potholes per km at start of analysis year
$\Delta CSAL$ =change in cumulative standard axles (msa) over time t in years	m =environmental coefficient (default value=0.025)
SNCK=modified pavement strength=(1+MSNR)	AGE3=age since last overlay or reconstruction (years)
MSNR=reduced modified structural number due to cracking	SNPK _a =adjusted structural number due to cracking at end of analysis year
m =environmental factor (value=0.04 for AC)	$\Delta ACRA$ =incremental change in area of total cracking during analysis year (percent)
	ΔRDS =incremental change in standard deviation of rut depth during analysis year (mm)
	FM=freedom to maneuver index based on carriageway width (in m and AADT)
	AADT=two-way traffic flow (vehicles/day)
	ΔNPT =incremental change in number of potholes per km during analysis year
	NPT _o =number of potholes per km at start of analysis year
	ΔRI =total incremental change in roughness during analysis year (m/km IRI)
	RI _o =roughness at start of analysis (m/km IRI)
	K_{gm} =calibration factor for environmental component of roughness (default value=1.0)
	$K_{cta}, K_{cpa}, K_{cti}$ =calibration factors for respective models.

Aggarwal et al. (2005) The main objective of this study has been to develop PMMS for the NHs to assist the responsible bodies in maintenance of NHs. The study has been conducted on five NHs in the states of Uttaranchal and Uttar Pradesh within two districts of Uttaranchal i.e. Haridwar and Dehradun and two districts of Uttar Pradesh i.e. Muzaffarpur and Saharanpur. The roads have been divided in 22 sub-sections. This division of the sections has been done according to their various characteristics like traffic pattern, pavement composition and crust thickness. These sections are almost similar within themselves but vary considerably from one another in terms of traffic characteristics and pavement characteristics. Roughness has been measured in terms of IRI by conversion of unevenness index of pavement. Serviceability Levels for road pavements has been used in 3 levels. Serviceability level has been used because road pavements can not be maintained at highest levels of serviceability. So, as per MORT&H (2001) guidelines. There has been four alternatives used in M&R modelling. One has been routine maintenance and others have been widening as per the traffic.

Table 3.3 Maintenance Serviceability levels for pavements

Sr. No.	Servicability Indicator	Serviceability Levels		
		Level 1	Level 2	Level 3
1	Roughness by Bump Integrator(max. permissible) Equivalent IRI	2000 mm/km 2.8 m/km	3000 mm/km 4.0 m/km	4000 mm/km 5.2 m/km
2	Potholes per km (max. number)	Nil	2-3	4-8
3	Cracking and patching area (max. permissible)	5 percent	10 percent	10-15 percent
4	Rutting – 20 mm (maximum permissible)	5 mm	5-10 mm	10-20 mm

Sudhakar (2009) The study has been done on the 36 sections of urban roads in the state of Tamilnadu. The pavement is flexible pavement with BC and SDBC resurfacing. Data for distresses Cracking, Ravelling, Patching, Potholes, Rutting, Edge breaking, Roughness has been gathered. The 4 alternatives including base scheduled alternative

has been assigned to the pavement model. The alternative 3 has been found to be optimum. On an average of 2 years renewing of pavement has been predicted.

Jain et al. (2013) The study has been conducted on a NH and an expressway. The study are the Noida-Greater Noida Expressway and Ghaziabad to Hapur NH. The NH has been divided in eight sub sections and the Expressway is subdivided in five sub sections. The expressway is a 6-lane divided carriageway while NH is a 4-lane divided carriageway road. The interventions have been selected according to the desired level of serviceability. BBD has been used for structural evaluation of pavements. The factors that has been considered for evaluation include Cracking, Ravelling, Potholes, patching and Rutting. There have been 5 alternatives used with different intervention criteria. First alternative included routine maintenance while alternatives included resealing, thick overlay, resealing overlay and overlay, and strengthening respectively. From NPV/CAP value it has been concluded that alternative 3 was best for Expressway while alternative 2 was best for NH.

Shah et al. (2013) The study has been conducted on the urban roads of Noida. The study road sections are of 120 km length in total (60 km on each side). The road sections are divided carriageways with 4 lanes as well as 6 lanes. The pavement has been flexible pavement. The data has been collected by visual inspection and from the responsible authority responsible for the roads. There have been five preventive interventions including base scheduled intervention while others have been responsive interventions. The R^2 , T-test, Chi-square test, null hypothesis has been done to validate the model. R^2 has been come out as 0.734.

Shah et al. (2013) The 10 sections in the city of Noida has been considered for the study with a length of 29.92 kms. The methodology implemented has collection of distresses data, distress indexes of each section individually and thereafter development of Overall Pavement Condition Index. Then this OPCI has been used to select the required M&R strategy. Pavement has been rated on the scale of 0 to 100. The minimum & maximum values of cracking(longitudinal) has been predicted 8.3 % & 11.86 %; ravelling has been predicted 9.58 % & 29.24%; pothole has been predicted 1 & 6 in numbers; Roughness

has been predicted as 2.08 IRI & 5.41 IRI. There has been recommendation for further study before implementing this OPCI index.

Vyas et al. (2014) The objective of the study has been to find out the best M&R alternatives using HDM-IV model for a State Highway section in the state of Karnataka. The different pavement distresses have been measured and the bowl deflection data has been also collected. There has been traffic analysis for all the 8 sections and basic characteristics of the vehicle fleet has been mentioned. Total of four alternatives has been used including the base periodic alternative where an annual intervention has been implemented, other interventions has been based on pavement deteriorations i.e. upon total damaged area and roughness. The alternative 1 has been found to be the most optimum maintenance strategy in economic analysis.

Shah et al. (2016) The study has been conducted on the urban roads in the state of Uttar Pradesh. The basic aim of the study was to attain a desirable IRI at minimum costs. The data that has been collected included the distresses of pavement, pavement composition, pavement age and rehabilitation or reconstruction information. There has been six alternatives used in the Maintenance and Rehabilitation strategy. First one is scheduled periodic, second is total damage area responsive and the other are Roughness responsive. The different intervention levels have been used for various interventions. The conclusions conclude that it depends on the planner to select/adopt best maintenance alternative and also the maintenance budget required for a road network.

Vaghela et al. (2017) The study has been done in the city of Rajkot. The 4 road sections of the urban road network have been used to develop a PMMS. The IRI has been calculated from unevenness index. The Remaining Service Life of the road sections has been determined. Two alternatives for M&R has been used, one is routine maintenance while other one is responsive maintenance work standard. The RSL has been determined between 8-10 years for different road sections. So there has to be a very strong and sound maintenance strategy.

Chopra et al. (2017) The aim of the study has been to develop a PMMS model with the help of HDM-IV to determine the optimum M&R strategy for urban roads in the city of

Patiala. The data was collected under four categories namely Road network data, Traffic volume and vehicle composition data, M&R works data and lastly RUC data. 4 sections has been selected from the city urban roads. Distress survey and traffic survey has been done.

Table 3.4 Proposed M&R alternatives

M&R Strategy	Works Standard	Description of Work	Intervention Level
Base Alternative	Routine	Crack Sealing	Scheduled annually
		Patching	Scheduled annually
Alternative 1	Resealing + Thin Overlay	Provide 25 mm DBSD	Total damage area > 8% of total area
		Provide 25 mm BC	Roughness ≥ 4 , ≤ 5.8 IRI
Alternative 2	Thick Overlay	Provide 40 mm BC	Roughness ≥ 5.8 , ≤ 8 IRI
Alternative 3	Reconstruction	Provide (200 mm Wet Mix Macadam + 75 mm Dense Bituminous Macadam + 40mm Bituminous Concrete)	Roughness ≥ 8 IRI

Alternative 1 has been found out to be the optimum Maintenance & Rehabilitation strategy for all the sections.

Aditya et al. (2018) The has been carried out on the urban roads in the city of Patiala in north India. The distress and pavement characteristics data for the fifteen urban road sections has been collected for the 3 years continuously. Four sub parts has been divided of these 15 sections according to their homogeneity. The celebration of HDM has been done to get optimum results. For cracking variability has been between 2 to 18 percent and for ravelling it has been 2 to 10 percent. The R^2 for cracking and ravelling distress model has been 0.997 and 0.973 respectively.

Aditya et al. (2018) The main objective of the study has to develop a distress model for rutting and roughness. The has been carried out on the urban roads in the city of Patiala in north India. The distress and pavement characteristics data for the fifteen urban road sections has been collected for the 3 years continuously. Four sub parts has been divided of these 15 sections according to their homogeneity. Celebration of the model has been done for 4 groups of road sections. Different regression validation has

been performed on the predicted data. Celebration for rutting has been 2.63 - 2.84 while for roughness, it's been 2.01 - 2.75.

Chopra et al. (2018) The genetic Programming has been used in the prediction of pavement distresses for urban roads. There have been 5 models for 5 different distresses. The data has been gathered for the city of Patiala with the BBD and the visual surveys of distresses for 4 years. 16 road sections have been taken for the study. The model has been fit for 0.1 to 0.85 ESA and MSN between 2 to 4.5.

Table 3.5 Architecture of the GP model

Parameters	Values	Description
Initial population size	Dataset	Dataset-1 is of 16 instances consisting of data gathered in 2012 and 2013.
Function set	$+$, $-$, $*$, $/$, $\text{sqrt}()$, $\text{tanh}()$, $\text{pow}(x, y)$, $\text{log}()$, $\text{exp}()$, $\text{pow}(x, 2)$, $\text{fabs}()$	Set of functions used
Training percentage	70	—
Selection method	Tournament	—
Tournament size of replacement	3	—
Maximum generations	100000	Maximum number of iterations
Crossover	0.8	Probability of crossover
Mutation	0.04	Probability of mutation
μ	200	Population size
λ	250	Number of children produced
Fitness functions	R^2 RMSE	Coefficient of determination Root mean square error

Table 3.6 GP model for various Distresses

	Values
Model 1 (cracking progression)	$CA_j = (1/MSN_i)((MSN_i \times CA_i) + ((e^{((CA_i \times e^{-ESA_i})/(AGE_i))})/AGE_i) + ((2 MSN_i + AGE_i + e^{ESA_i})/CA_i) + 1),$ <p>where CA_j is the cracking of the next year, CA_i is the cracking of the previous year, MSN_i is the modified structural number of the previous year, AGE_i is the age of the pavement before the start of the analysis year, and ESA_i is the number of equivalent standard axle repetitions in the analysis year (in millions)</p>
Model 2 (ravelling progression)	$RA_j = 1 + RA_i + ((AGE_i(1 + ESA_i) + 2(RA_i + e^{\sqrt{AGE_i}}))/ (RA_i(ESA_i + AGE_i))) + \tanh(AGE_i^2((AGE_i \times ESA_i) - RA_i)),$ <p>where RA_j is the ravelling area of the next year and RA_i is the ravelling of the previous year, AGE_i is the age of the pavement before the start of the analysis year, and ESA_i is the number of equivalent standard axle repetition in the analysis year (in millions)</p>
Model 3 (potholes progression)	$POT_j = \tanh(e^{\tanh(CA_i)} + RA_i + POT_i) + POT_i - ESA_i - \tanh(POT_i - \tanh(POT_i - \tanh(\sqrt{\tanh(AGE_i)}) - AGE_i)),$ <p>where POT_j is the pothole of the next year (number per km), POT_i is the pothole of the next year (number per km), CA_i is the cracking of the previous year, RA_i is the ravelling area of the previous year, AGE_i is the age of the pavement before the start of the analysis year, and ESA_i is the number of equivalent standard axle repetition in the analysis year (in millions)</p>
Model 4 (rutting progression)	$RD_j = RD_i + DF + \tanh(RD_i(MSN - DF - 1)/(\log(MSN/ESA_i) + CA_i + AGE_i + (RD_i/2 MSN + \log(MSN))))),$ <p>where RD_j is the rutting of the next year, RD_i is the rutting of the previous year, MSN_i is the modified structural number of the previous year, AGE_i is the age of the pavement before the start of the analysis year, DF is the drainage factor, CA_i is the cracking of the previous year, and ESA_i is the number of equivalent standard axle repetitions in the analysis period (in millions)</p>
Model 5 (roughness progression)	$IRI_j = 1.254(((ESA_i \times AGE_i \times IRI_i)/(ESA_i \times RD_i \times dNPT \times AGE_i) + (12.048 \times IRI_i) + (ESA_i^3 \times AGE_i)) + (IRI_i)\sqrt{ESA_i}),$ <p>where IRI_j is the roughness of the next year, IRI_i is the roughness of the previous year, ESA_i is the number of equivalent standard axle repetitions in the analysis year (in millions), AGE_i is the age of the pavement before the start of the analysis year, and $dNPT$ is the change in the number of potholes during the analysis year, RD_i is the rut depth in the previous year</p>

3.2 STUDIES DONE ABROAD

Kerali et al. (1998) gave an overview of the HDM-IV model which has been an updated version of HDM-III. The new version has been developed so as to complete the requirements of industrialised countries. This has been done to cope with traffic congestion, wider range of pavement types and climatic effects. Existing relationships of different entities has been updated and new relations has been introduced. A new set of vehicles has been introduced. The road work has been divided in routine maintenance, periodic maintenance, special works and development. There have been some additional models in HDM-IV like road safety, vehicle emissions & Energy balance. A new calibration facility has been provided for smooth adaptation of the conditions.

Jorge et al. (2012) The study has been conducted on the urban roads in the Viseu municipality of Portugal. There have been 67 sections with total of 141.2 km length. The model has been developed to substitute the existing AASHTO model due to recent Portuguese legislation. The warning levels has been set for various distresses i.e. 20% by area for cracking and surface disintegration, 20mm mean rut depth for rutting, 5500mm/km IRI for longitudinal roughness. There has been total 9 M&R actions and 6 interventions in the model with a constraint that each year only one of the M&R operations has to be performed.

Odoki et al. (2013) have developed HDM-IV for the use of DfT in England. The work has been done from year 2006 to year 2009 in the university of Birmingham. The England has many classes of roads with length of 299166 km. The HDM-IV model has been used with the purpose of planning maintenance and the budget needed to carry these maintenances. The level 2 calibration of HDM-IV has been done [Bennet, 2000]. The pavement treatment has been divided in the parts i.e. surface improvement, resurfacing, strengthening with different interventions. Conclusions included that a minimum of four-year data can improve the credibility of the model.

Ognjenovic et al. (2015) The HDM-IV model has been developed from the data of Brazil and South Africa. So, in order to use the model, the has to be calibrated according to the local conditions i.e. climatic, traffic characteristics, soil type etc. The search has

been carried between year 2010 to 2014 in Macedonia. The research has been done on the 1 km sections and 300 m stretches. This is because the selected stretch should not have any cracks or a very minor crack can be there. Different temp and precipitation levels has been discussed to predict the crack initiation. The calibration factor 0.59 has been used for crack initiation because the values of default factors has been very high as compared to actual observed values. This has been predicted that after 6 to 8 years of the construction the cracking will appear.

CHAPTER – 4

DEVELOPMENT OF PMMS USING HDM-IV MODELLING

4.1 GENERAL

HDM-IV has been used to develop the PMMS of the urban roads. Basically in this chapter, the prediction of Residual Service Life (RSL) of pavement, the distress prediction for next 15 years from the observed data and the M&R strategy for the pavement with various alternatives has been done. Also, the data used in the process has been shown in different tables. A proper and precise methodology has to be developed in order to develop an optimum PMMS.

4.2 SELECTION OF ROAD NETWORK AND DATA ACQUISITION

In the present study, Urban Road network data has been collected. The data has been collected for the city of Noida (Uttar Pradesh) in the northern part of India. The selected roads are homogenous in geography, environment and climate. The data set for 21 road section has been collected and has been shown in the table 4.1 ,4.2, 4.3.

In table 4.1, The details of the road section like no. of lanes, length of road section, carriage width, design speed drainage conditions have been shown.

In table 4.2, The pavement survey data been shown which includes Structural evaluation with BBD i.e. deflection in mm, all the distresses, Modified Structure Number (MSN), Average Annual Daily Traffic (AADT).

In table 4.3, The details of the traffic have been given i.e. the percentage of every type of vehicle on a particular road section has been given.

Table 4.1 Road Section Details (Year 2011)

Section Code	No. of Lanes	Length in km	Carriageway Width (m)	design Speed	Drain Condition	Long. Slope(m/m)	CBR (%)
R1	6	3.8	10.5	80	Fair	0.003	3.03
R2	6	3.5	10.5	80	Fair	0.003	2.2
R3	6	6	10.5	80	Fair	0.003	2.65
R4	6	7.5	10.5	80	Fair	0.003	6.9
R5	6	3.2	10.5	80	Fair	0.003	3
R6	6	2.2	10.5	80	Poor	0.003	5.2
R7	6	2.4	10.5	80	Poor	0.003	3.72
R8	6	3	10.5	80	Fair	0.003	3.2
R9	6	2.2	10.5	80	Poor	0.003	4.41
R10	6	2	10.5	80	Fair	0.003	3.51
R11	4	3.3	7	60	Poor	0.003	4.13
R12	6	1.8	10.5	80	Fair	0.003	2.62
R13	6	4	10.5	80	Fair	0.003	2.34
R14	6	2.3	10.5	80	Fair	0.003	2.75
R15	6	2.5	10.5	80	Fair	0.003	3.8
R16	4	3	7	60	Fair	0.003	4.9
R17	4	0.7	7	60	Poor	0.003	3.3
R18	4	0.7	7	60	Fair	0.003	2.93
R19	6	2	10.5	80	Fair	0.003	3.44
R20	6	3.2	10.5	80	Fair	0.003	4.27
R21	4	0.7	7	60	Fair	0.003	3.65

Table 4.2 Pavement Survey data

Section	BBD (mm)	Roughness (IRI)	Cracking	Ravelling	Pothole	Rutting	MSN	MT AADT
R1	1.024	2.41	6.81	2.77	0.5	2.04	3.24	64476
R2	1.214	4.03	9.57	3.44	1	13.89	2.52	27598
R3	1.308	2.41	9.13	9.52	0.5	2.77	2.63	35807
R4	1.087	3.36	14.6	4.49	1	14.72	3.99	33381
R5	1.211	3.21	7.375	3.53	1	7.5	2.92	24912
R6	1.153	3.11	15.13	18.36	0.5	14.44	3.61	20332
R7	0.913	2.54	8.74	11.12	1.5	3.61	3.72	16804
R8	1.807	3.29	10.97	5.21	0.5	13.47	2.36	19930
R9	1.081	2.99	13.1	11.23	1.5	10.55	3.57	18450
R10	1.552	3.03	7.94	5.66	1.5	11.11	2.69	10637
R11	1.751	2.6	7.44	6.01	0.5	9.76	2.69	12686
R12	1.194	2.55	6.61	4.78	1.5	13.33	2.77	7961
R13	2.084	2.01	10.42	4.12	0.5	9.62	1.78	2290
R14	1.861	2.61	8.19	3.86	0.5	10.22	2.13	6114
R15	1.944	3.51	13.42	3.98	1.5	13.69	2.46	1324
R16	1.914	1.77	12.72	4.95	1	9.92	2.76	3660
R17	1.398	3.88	6.53	3.86	0.5	13.99	2.78	3279
R18	1.520	4.05	5.92	8.62	1.5	11.89	2.51	6066
R19	1.618	3.2	4.72	4.75	1.5	12.43	2.6	5373
R20	1.542	3.03	6.42	3.75	1	10.38	2.93	18645
R21	1.339	3.23	6.39	3.14	1	6.69	2.97	7826

Table 4.3 Traffic Composition

Section	Car/Jeep/ Van	Mini Bus	Bus	Scooter/ M Cycle	Mini Truck	Truck	Tractor	Total
R1	62.65	0.46	0.83	32.95	0.96	1.61	0.54	100
R2	55.53	0.40	3.01	37.81	1.36	1.11	0.78	100
R3	64.16	0.59	1.24	30.69	1.50	1.53	0.29	100
R4	59.84	0.49	2.13	34.25	1.43	1.32	0.53	100
R5	61.79	0.30	2.54	42.86	0.63	0.46	0.14	109
R6	51.37	0.86	3.76	39.98	1.23	2.06	0.74	100
R7	46.38	1.04	1.37	43.46	3.70	3.03	1.03	100
R8	46.25	1.13	3.79	42.00	3.42	2.47	0.94	100
R9	40.64	0.38	2.07	50.25	3.30	1.41	1.95	100
R10	39.23	1.14	2.12	50.81	2.42	2.22	2.06	100
R11	39.40	1.41	2.84	52.07	2.34	0.89	1.05	100
R12	37.52	0.66	3.43	33.20	14.02	10.51	0.64	100
R13	52.83	1.12	1.03	36.73	4.60	2.52	1.17	100
R14	47.65	1.22	0.86	38.48	5.14	5.13	1.51	100
R15	33.67	0.77	0.45	36.48	17.80	7.85	2.97	100
R16	31.32	0.35	0.81	31.57	14.61	14.49	6.86	100
R17	43.12	3.12	3.64	36.30	4.60	4.82	4.40	100
R18	56.79	0.17	1.07	35.25	1.83	2.45	2.45	100
R19	49.03	2.70	1.74	41.38	1.93	2.48	0.74	100
R20	46.29	1.14	6.29	41.58	2.39	1.49	0.83	100
R21	43.65	0.32	1.30	49.72	3.95	0.91	0.15	100

4.3 PROPOSED METHODOLOGY

The HDM-IV model is optimum and accurate only when calibrated to the local conditions. The more precisely the distress models are calibrated, better and more accurate will be the results. It is necessary that calibration factors are chosen with proper care and according to the climatic conditions, pavement type, traffic characteristics. In this study the calibration factors have been taken from a past study that has same characteristics as the study are characteristics. 1.34, 1.40, 0.28, 0.84, 0.24, 0.52, 0.60 are the calibration factors that have been taken for Cracking initiation, Cracking progression, Ravelling initiation, Ravelling progression, Pothole initiation, Pothole progression, Roughness progression respectively. The validation of the model as been done by comparing the observed field values with the predicted distress values.

4.4 HDM-IV MODELING

4.4.1 Road Network and Vehicle Fleet

A road network named as 'Urban Road' has been created. Twenty-One road sections with the Section ID R1, R2, R3 and R21 have been added to this network. Each section has been input with its characteristics. Climate zone has been selected as North India Plain for the study area. The vehicle fleet data has also been added. The snapshots of HDM-IV modelling have been shown in the figures below:

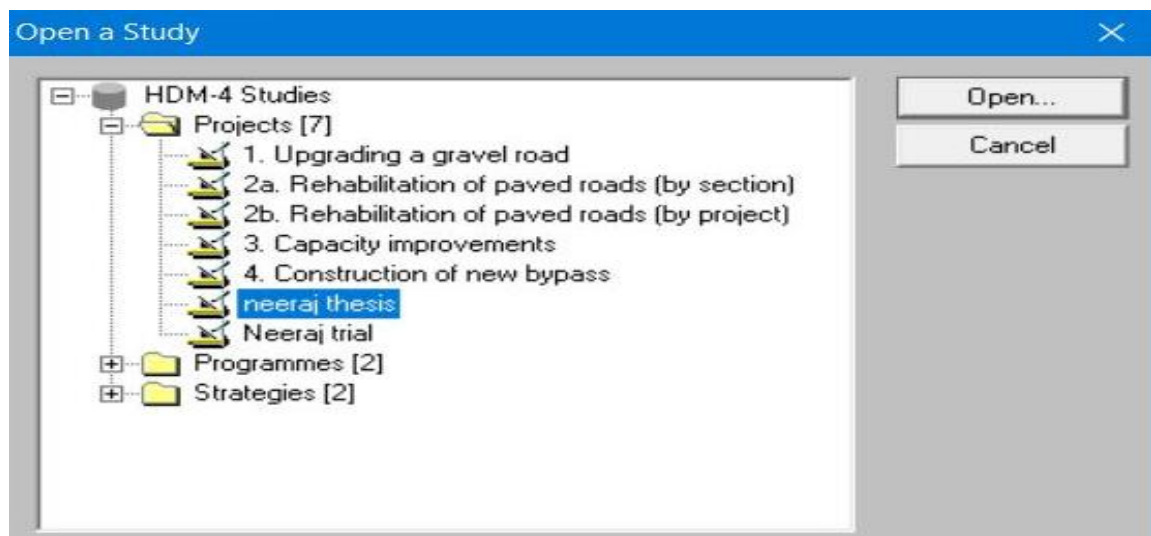


Figure 4.1 Creating and Opening a Project

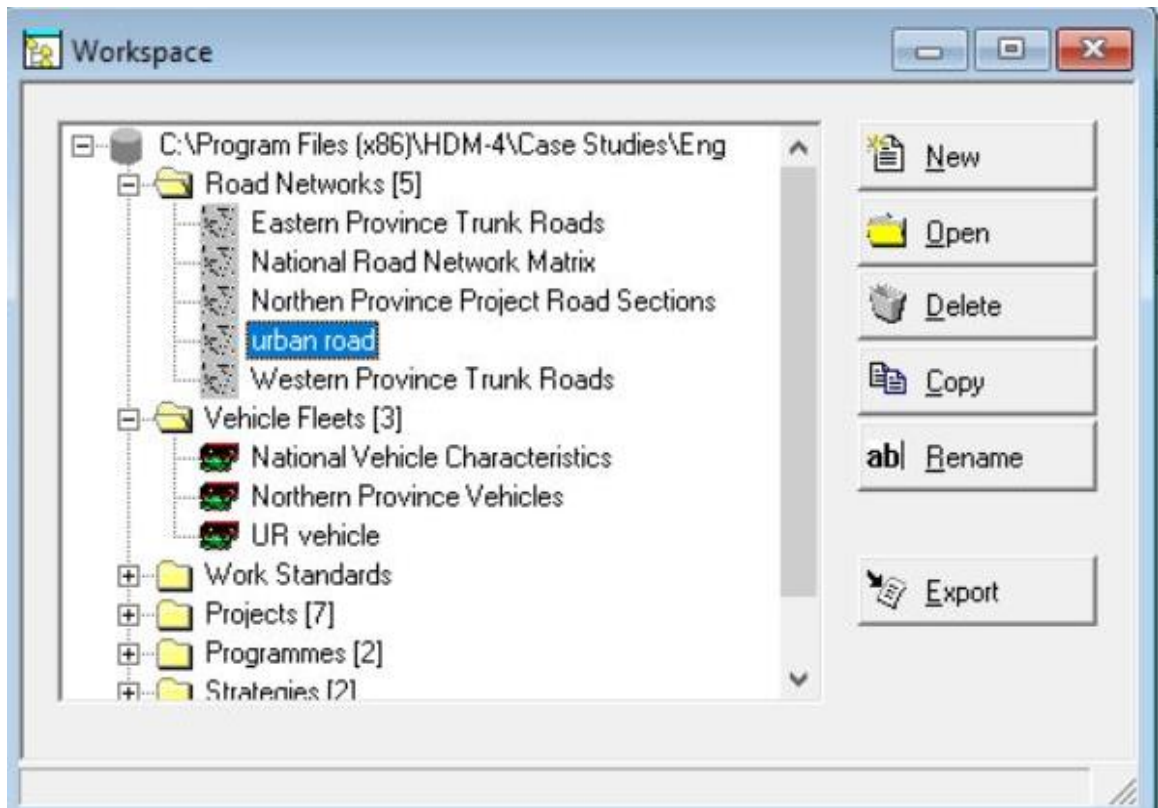


Figure 4.2 Creating a new Road Network

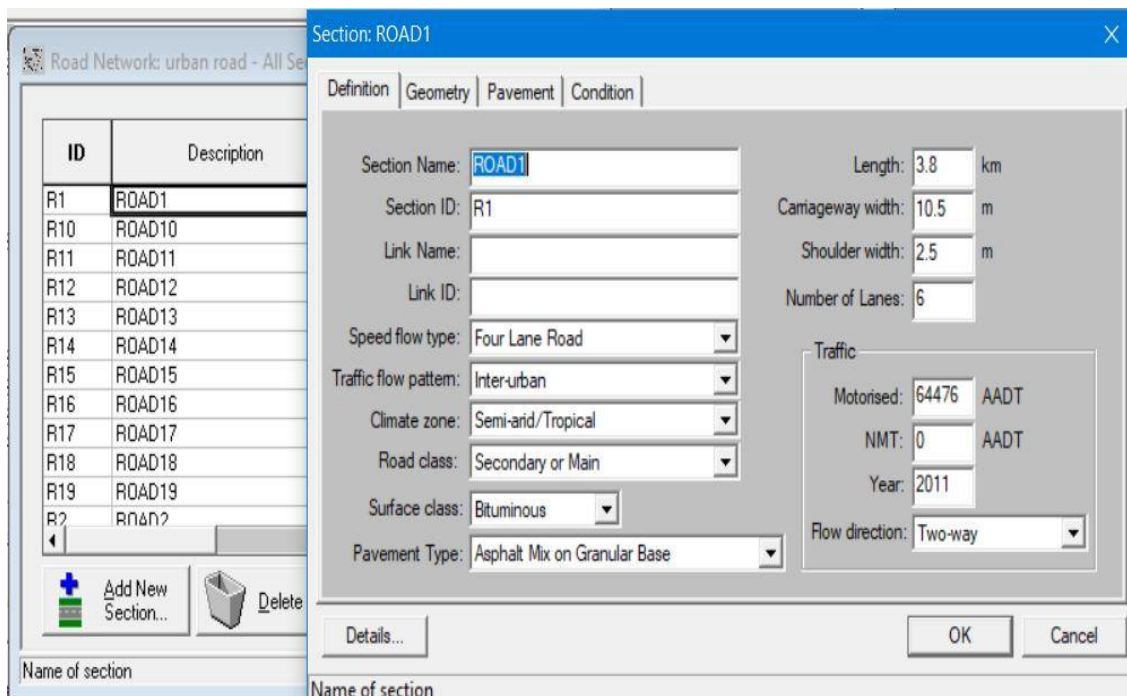


Figure 4.3 Definition of a Road Section

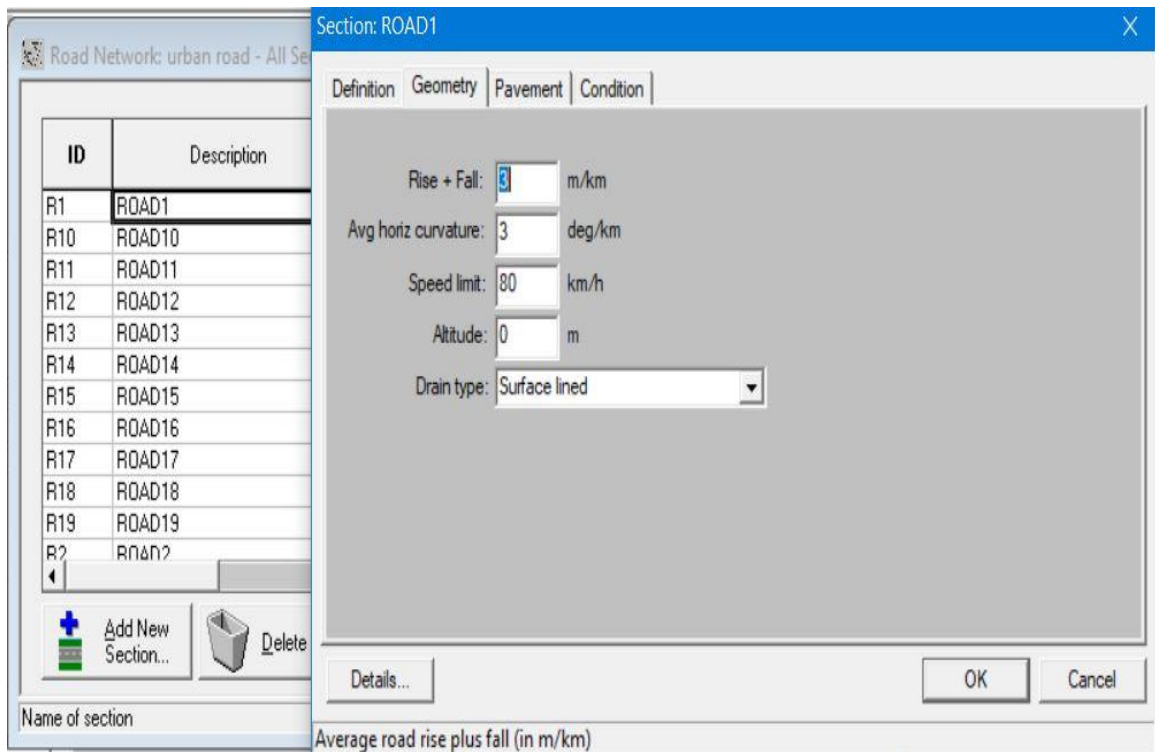


Figure 4.4 Geometric Parameters of a Road Section

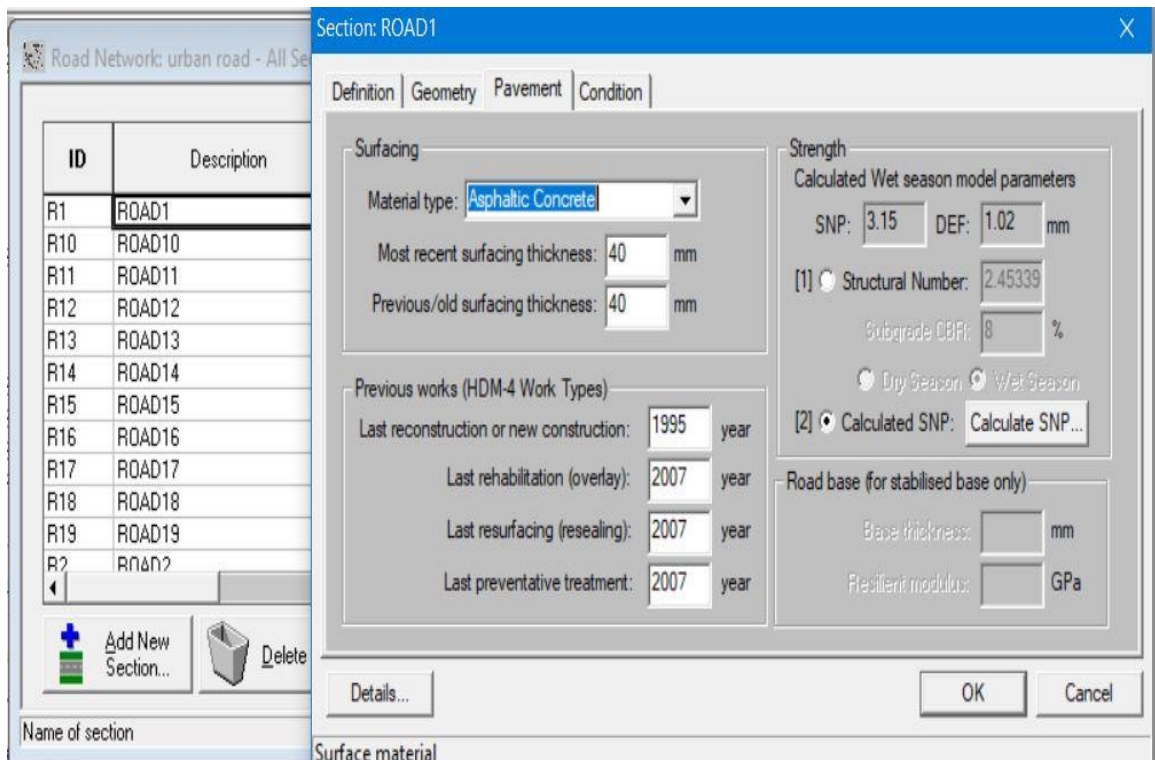


Figure 4.5 Pavement Crust Characteristics of the Section

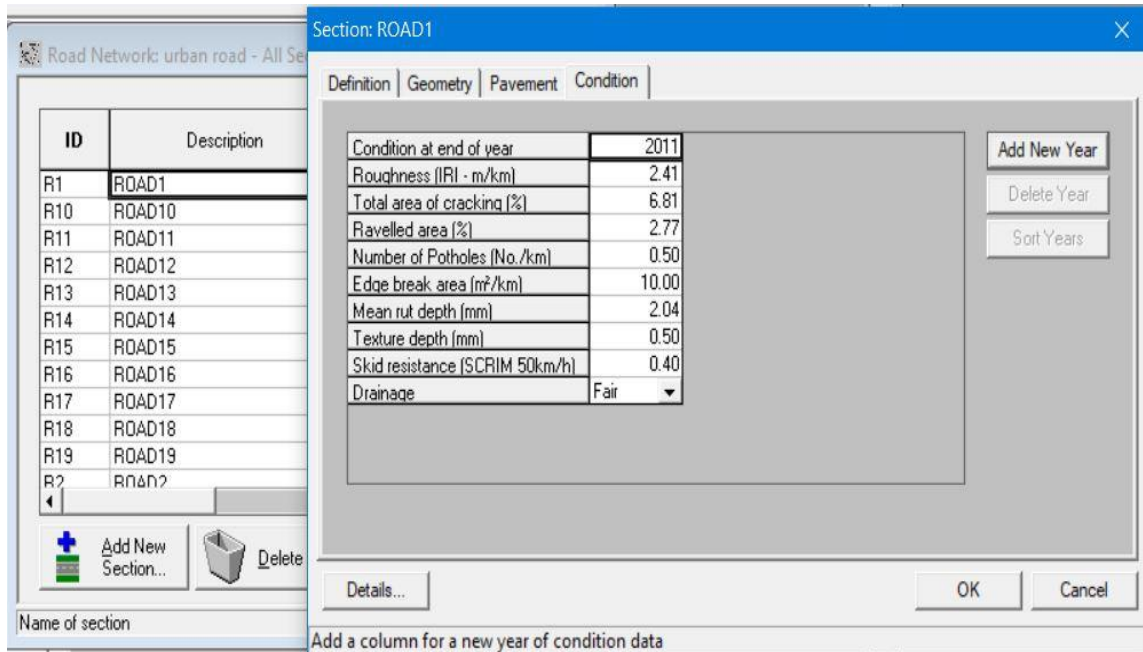


Figure 4.6 Observed Distresses of the section

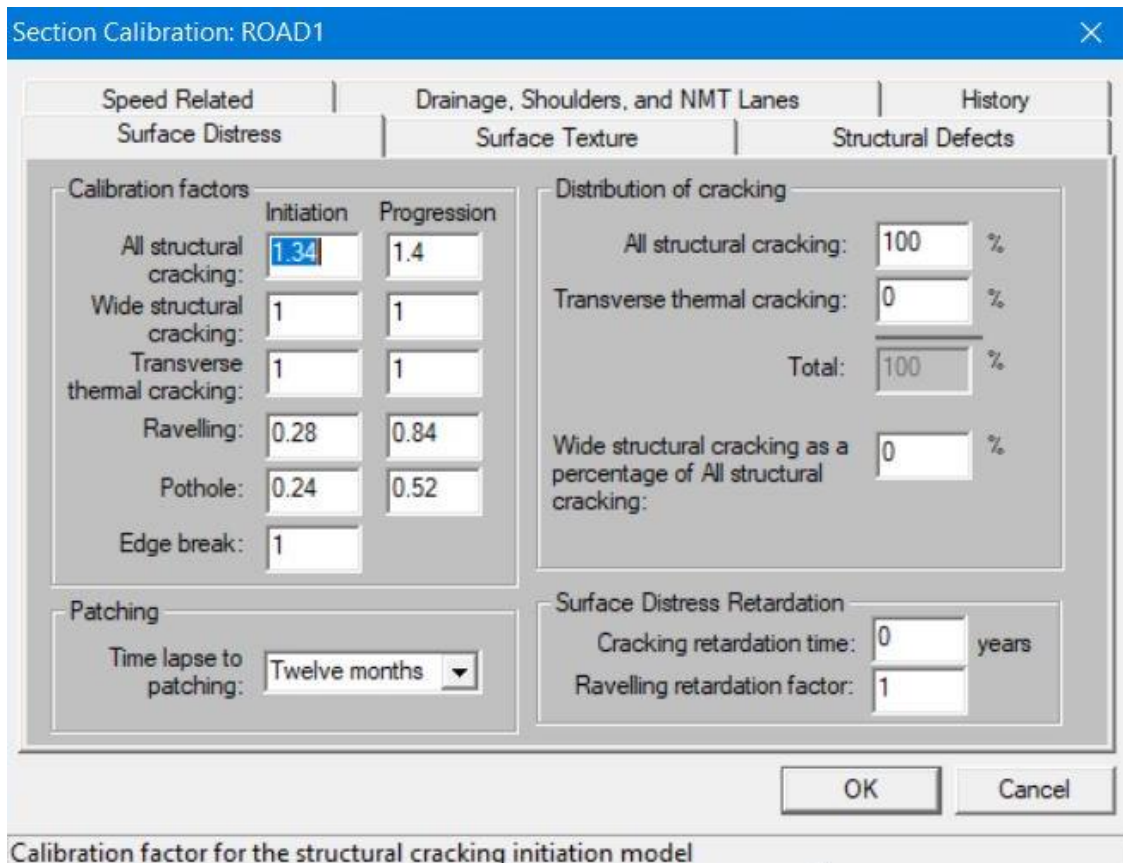


Figure 4.7 Calibration Factors for the Distresses of the section

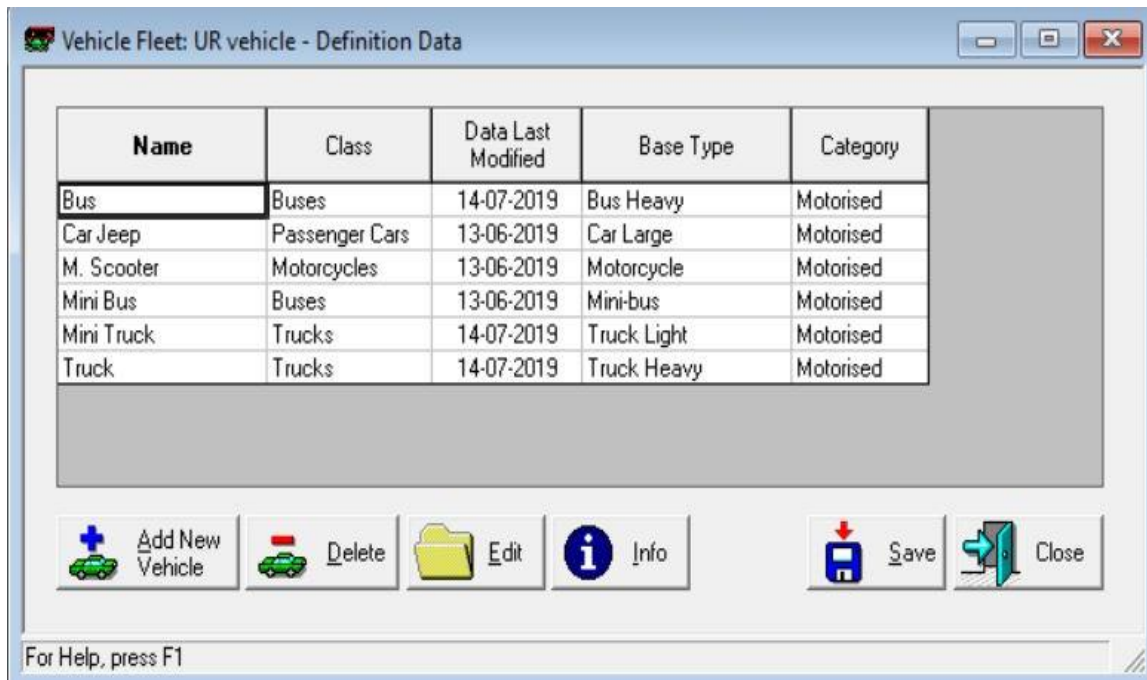


Figure 4.8 Vehicle Fleet Data Definition

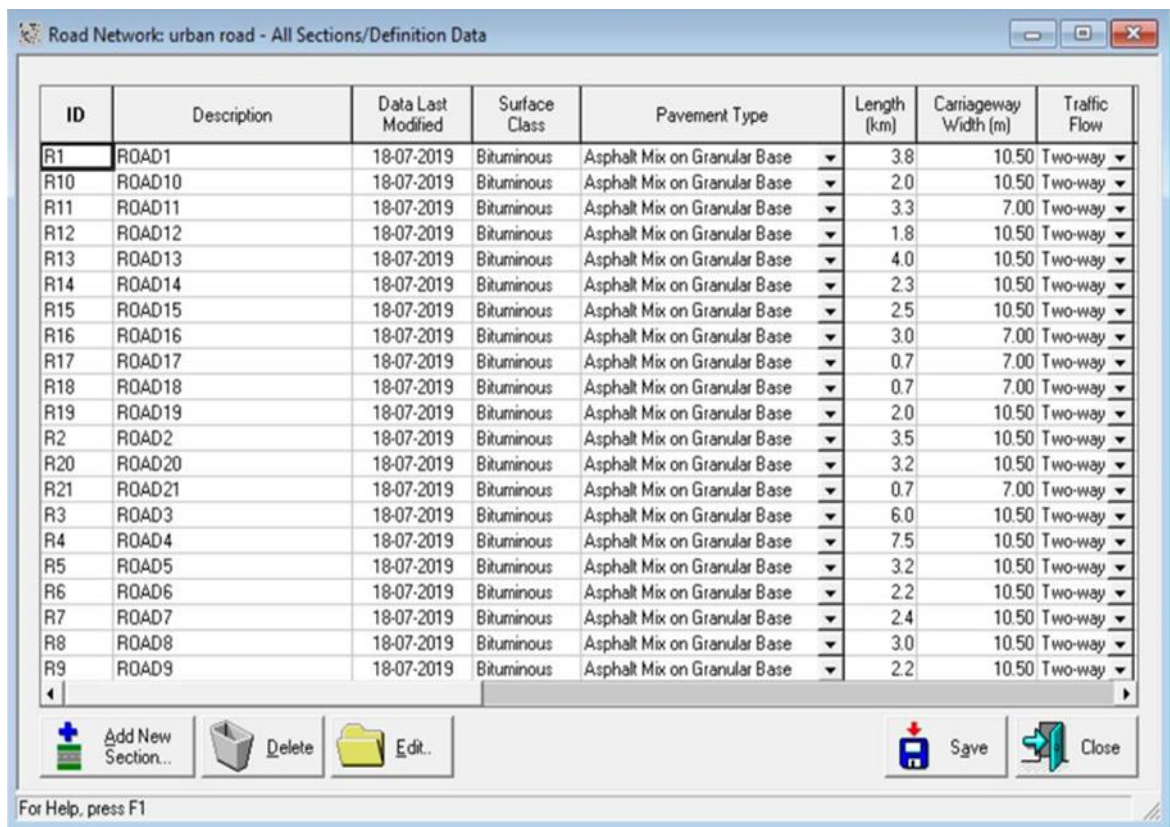


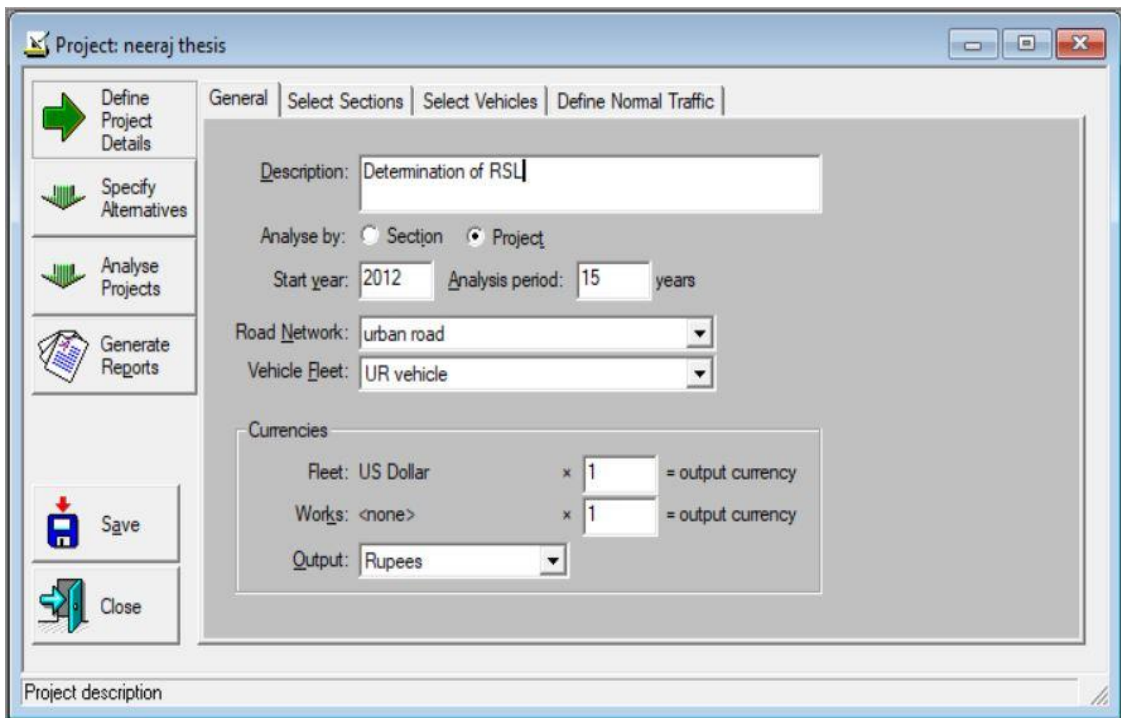
Figure 4.9 Road Sections after the Definition of Data

4.5 DETERMINATION OF RSL OF ROAD SECTIONS

The remaining service life of the pavement of each road section has been predicted. Remaining Service Life is the life of the pavement left in years if no Maintenance and Rehabilitation strategy is used., before there will a forced reconstruction of the pavement.

4.5.1 Input Data

The project consists of the road sections namely 'urban road' and 'UR vehicle' Vehicle Fleet. The intervention period has been taken as 15 years expect for one road section which had a way better RSL than the other pavements. Figure 4.10 show the general input of project for determination of RSL.



The screenshot shows a software window titled "Project: neeraj thesis" with a "General" tab selected. The interface includes a left-hand navigation pane with icons for "Define Project Details", "Specify Alternatives", "Analyse Projects", "Generate Reports", "Save", and "Close". The main area contains the following input fields:

- Description: Determination of RSL
- Analyse by: Section Project
- Start year: 2012 Analysis period: 15 years
- Road Network: urban road
- Vehicle Fleet: UR vehicle
- Currencies:
 - Fleet: US Dollar x 1 = output currency
 - Works: <none> x 1 = output currency
 - Output: Rupees

Figure 4.10 General Input for determination of RSL

4.5.2 Selection of Road Sections and Vehicles

All the twenty-one road sections of the road network and all types of the vehicles from the vehicle fleet has been selected for analysis purpose. Figures 4.11 and 4.12 show the same.

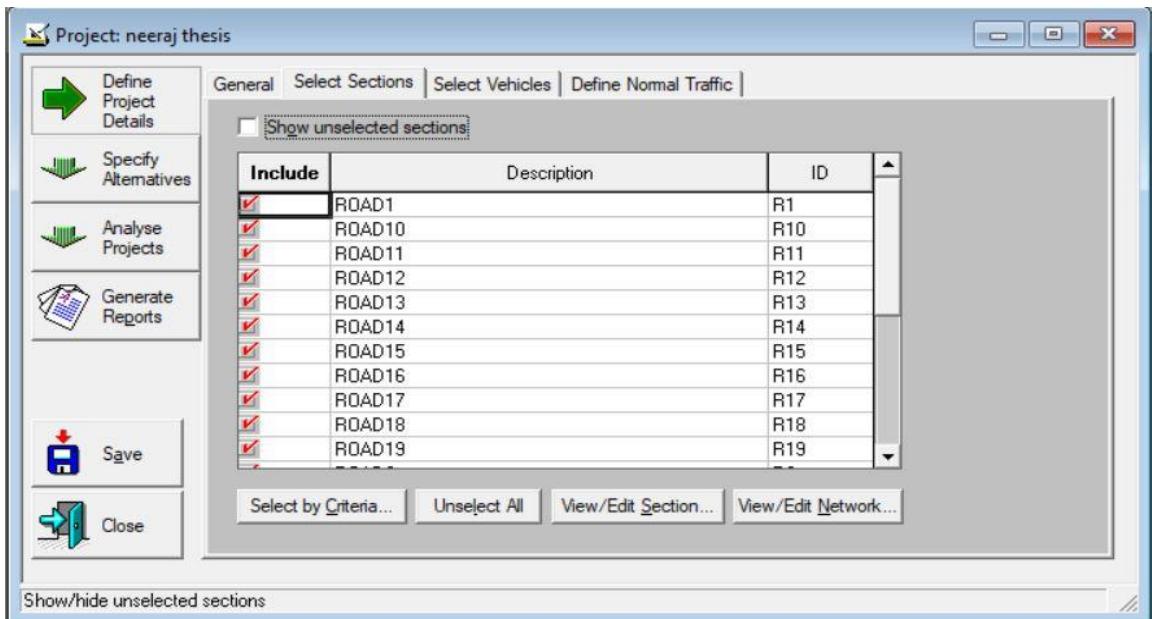


Figure 4.11 Road Sections for determination of RSL

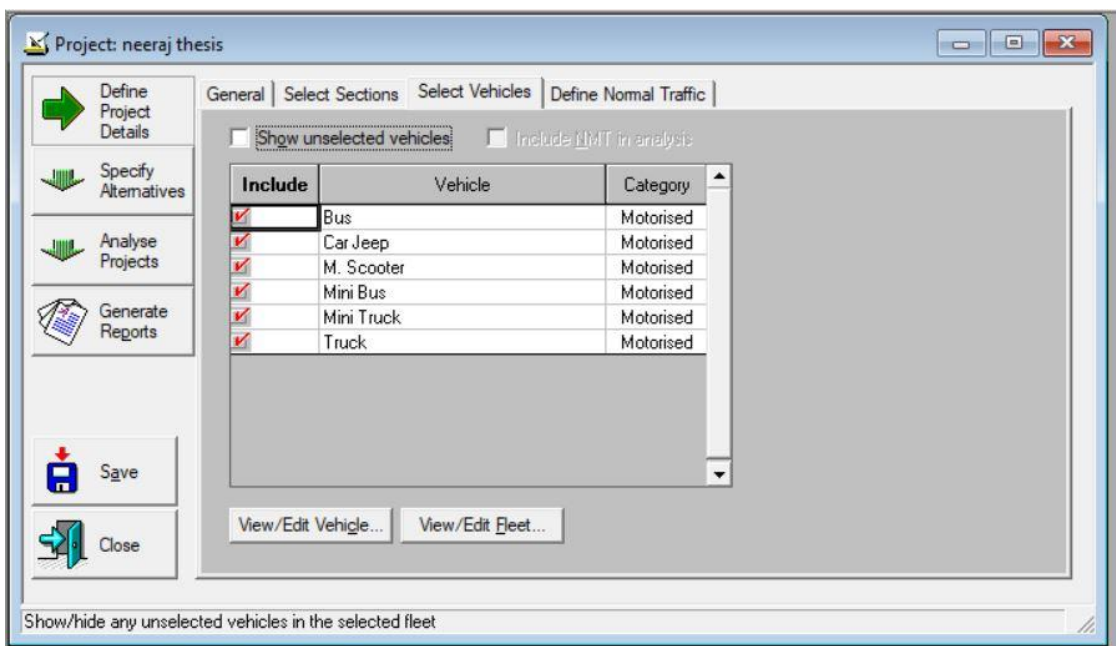


Figure 4.12 Selection of Vehicles for determination of RSL

4.5.3 Define Normal Traffic

Normal traffic details such as Vehicle Composition with annual growth rate has been input for each section. The following figure show the details of the motorised vehicles and normal traffic details of the road sections.

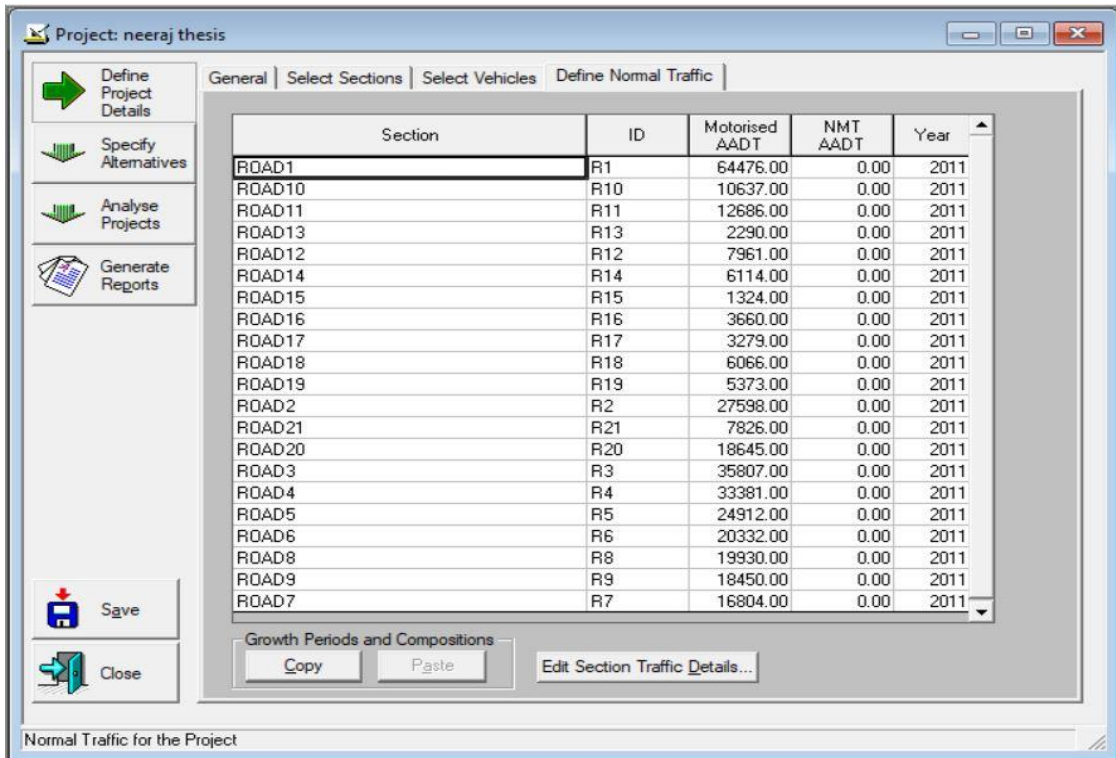


Figure 4.13 General features of the Traffic of Road Sections

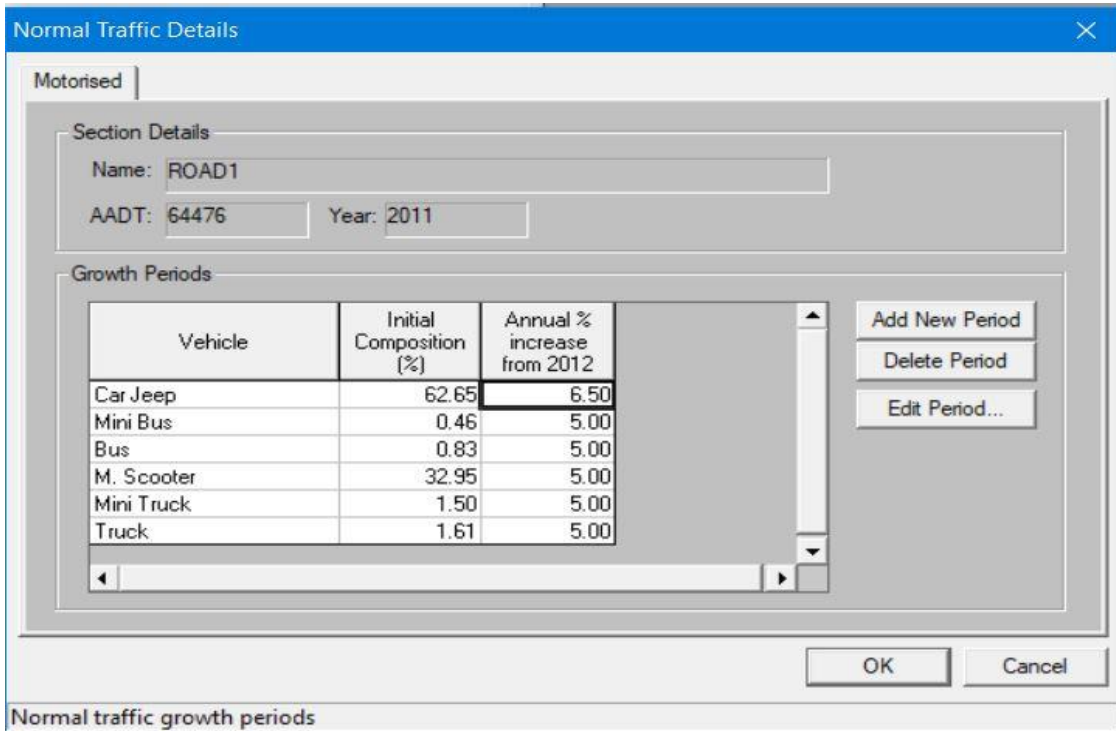


Figure 4.14 Normal Motorised Traffic Details for Road Section R1

4.5.4 Specifying Maintenance and Rehabilitation alternative

For RSL, 'Do Nothing uptill Reconstruction', a condition responsive M&R alternative has been defined for the project. Road roughness, play most crucial role in Pavement maintenance Management System. An intervention $IRI \geq 5$ has been taken keeping in mind the Level of Serviceability.

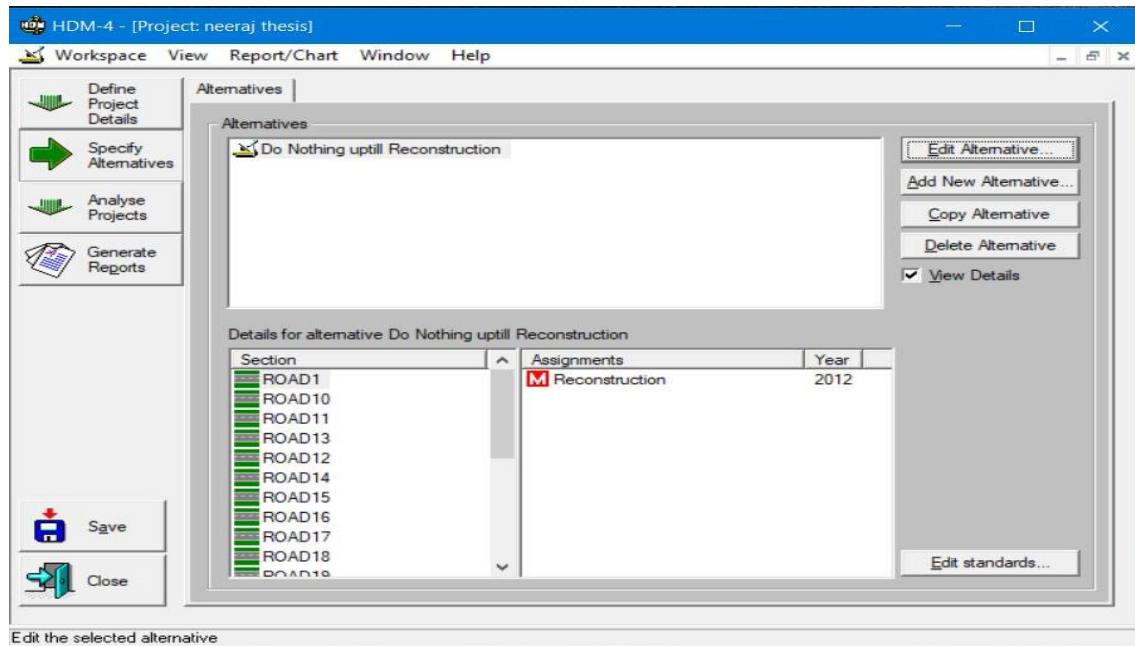


Figure 4.15 Normal Motorised Traffic Details for Road Section R1

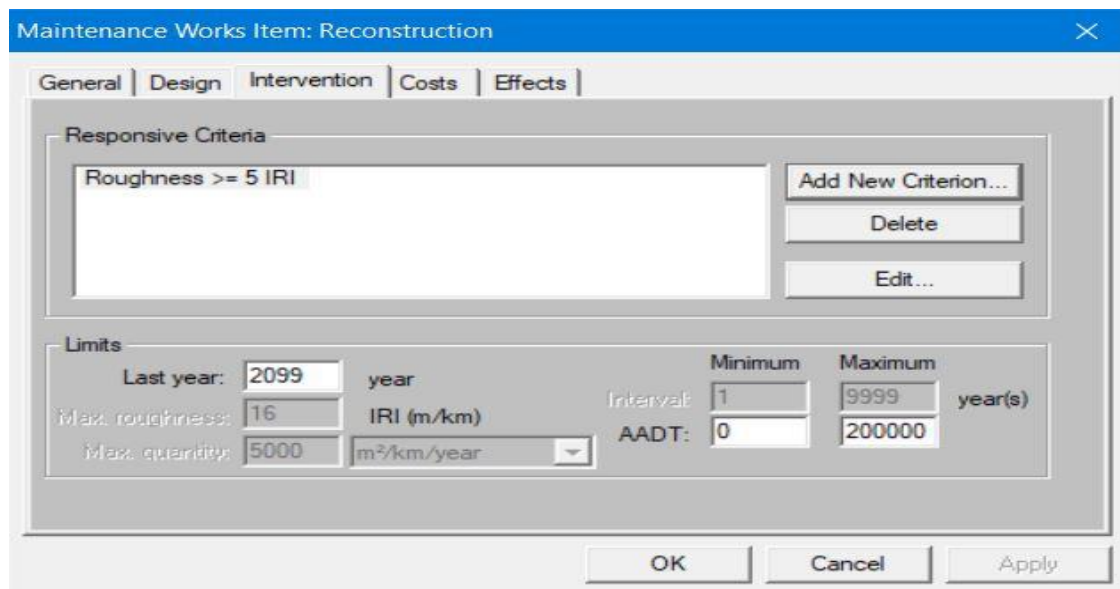


Figure 4.16 Intervention Criteria for M&R Work item

4.5.5 Project Analysis

The project has been run for 15 years for analysing the pavement deterioration of all the selected road sections. Figure 4.17 show the analysis execution of the project.

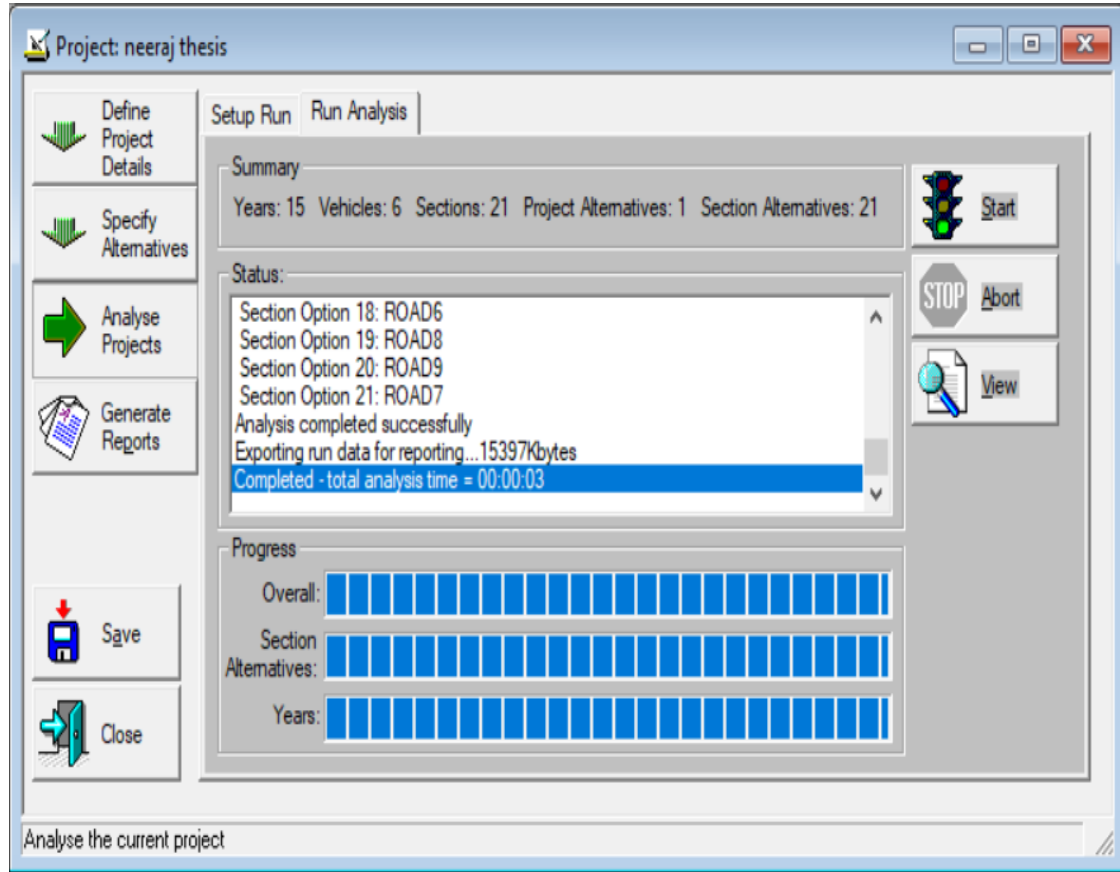


Figure 4.17 Run Analysis of Project for RSL

4.5.6 Roughness Progression

The roughness progress continuously, if it exceed the intervention value of IRI 5 in a year, then the reconstruction alternative shall be triggered for that year. The first time when this intervention will trigger and a sharp fall in average IRI will be observed that will be the RSL of that road section. The Roughness progression graphs has been shown in the figure 4.18 to 4.38.

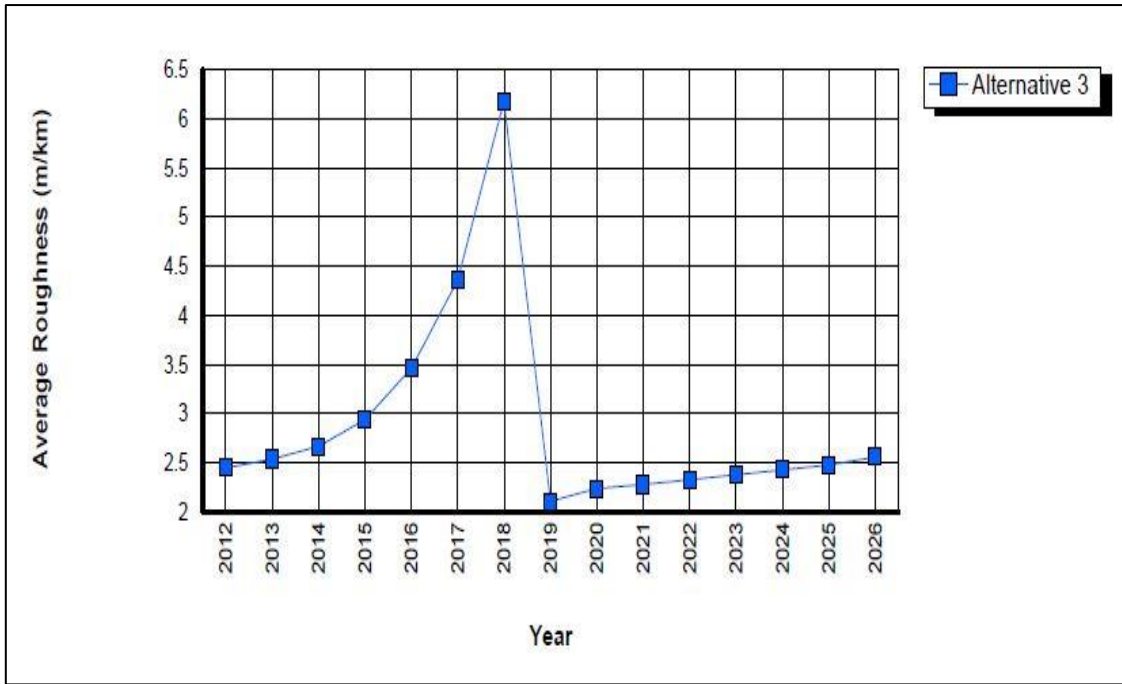


Figure 4.18 Roughness Progression for (R1) Road Section

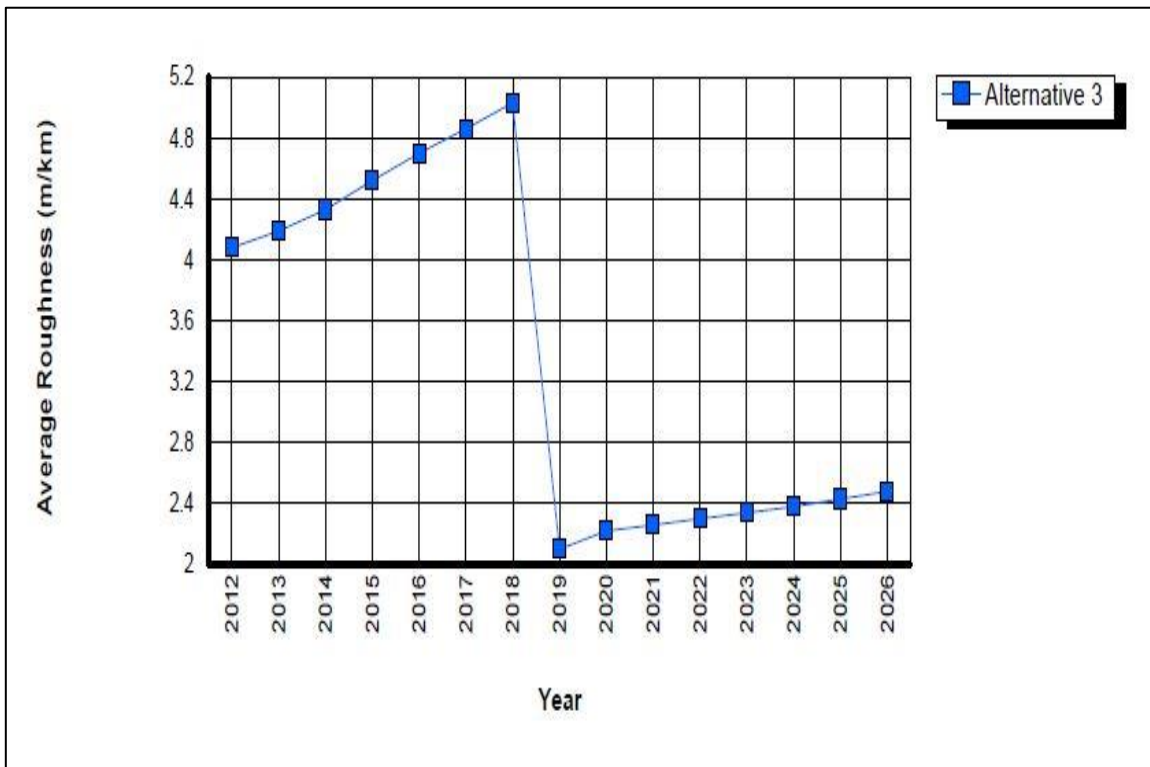


Figure 4.19 Roughness Progression for (R2) Road Section

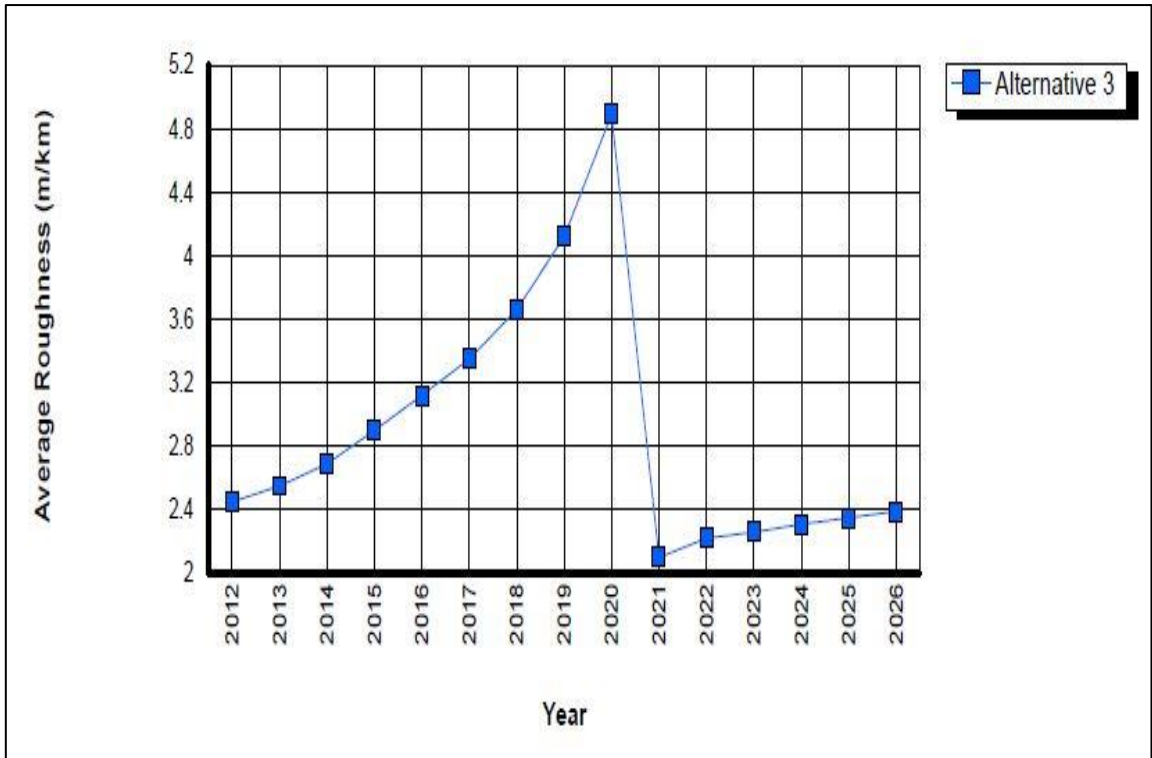


Figure 4.20 Roughness Progression for (R3) Road Section

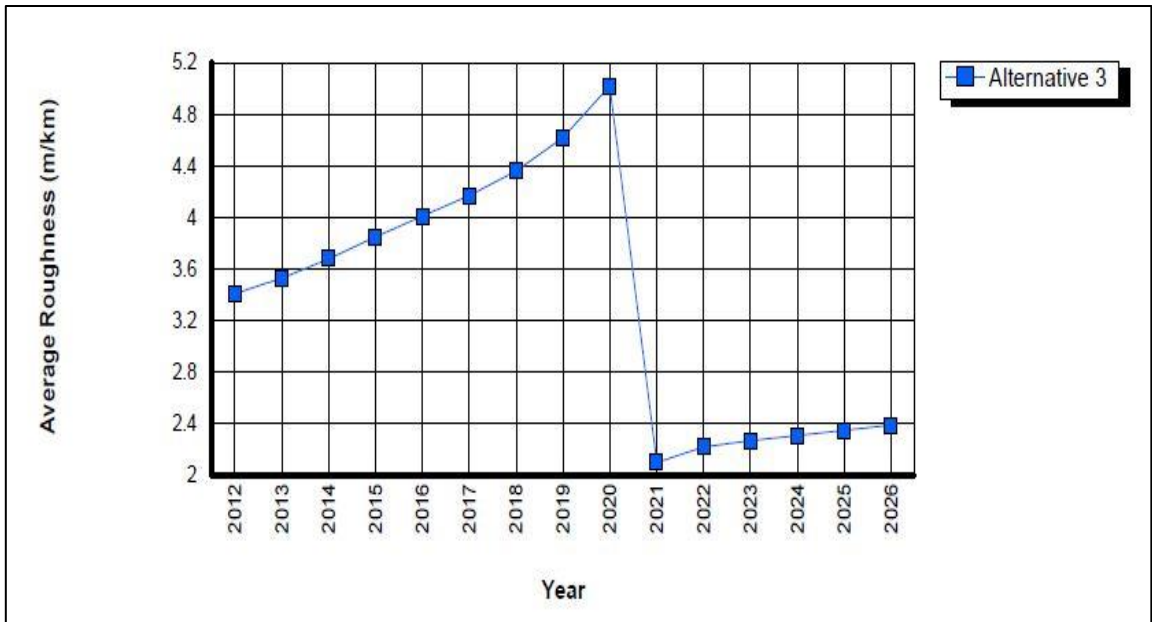


Figure 4.21 Roughness Progression for (R4) Road Section

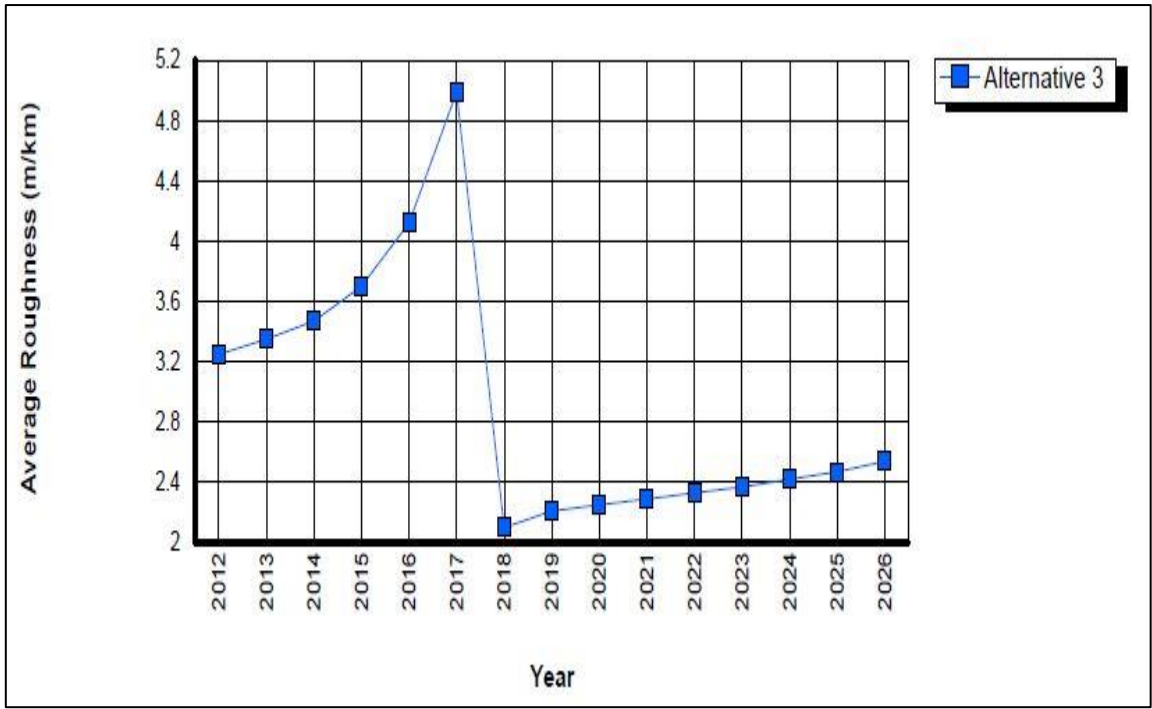


Figure 4.22 Roughness Progression for (R5) Road Section

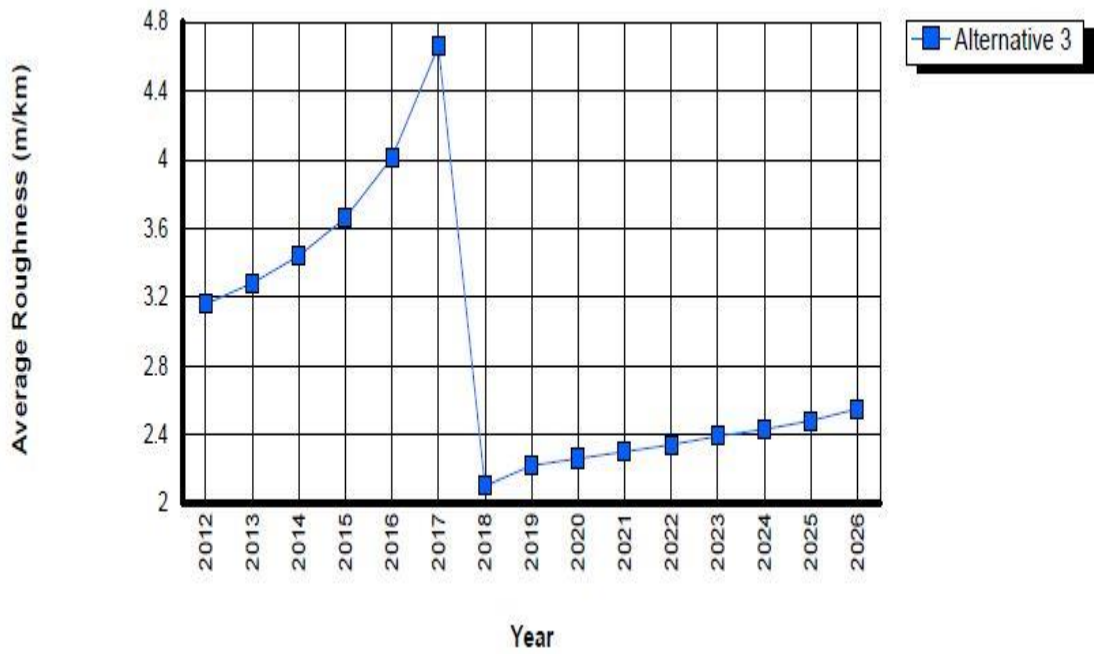


Figure 4.23 Roughness Progression for (R6) Road Section

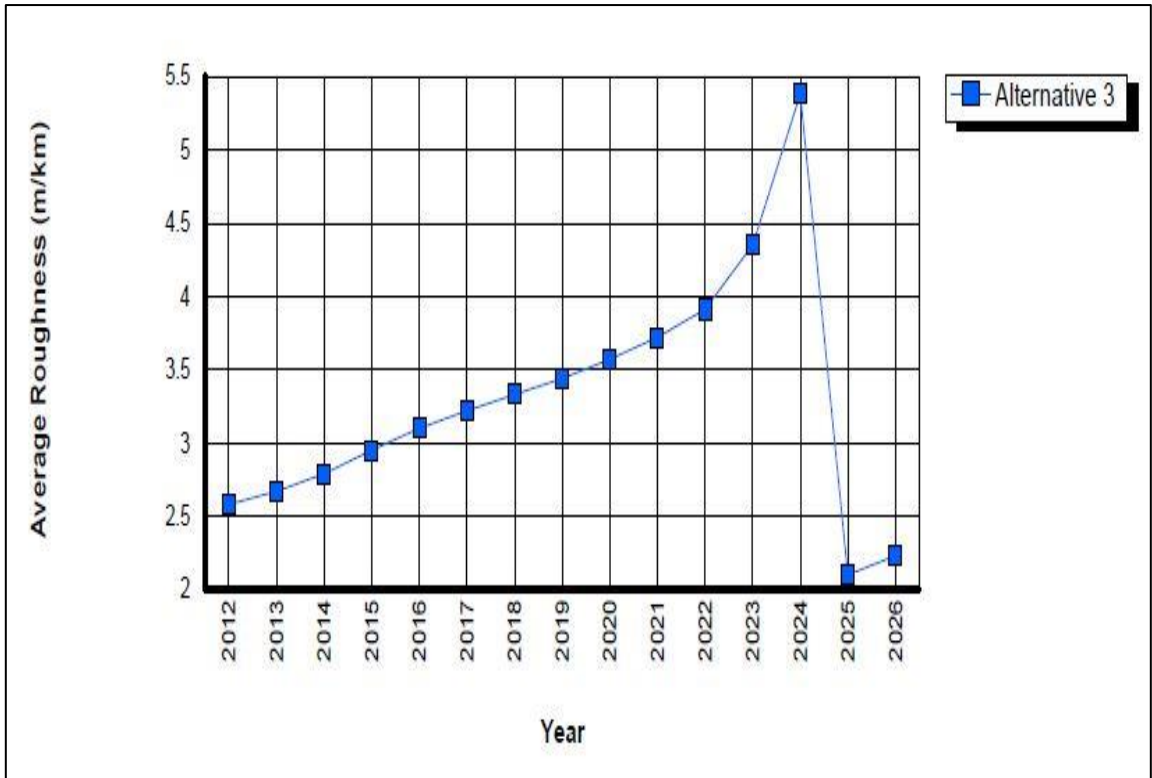


Figure 4.24 Roughness Progression for (R7) Road Section

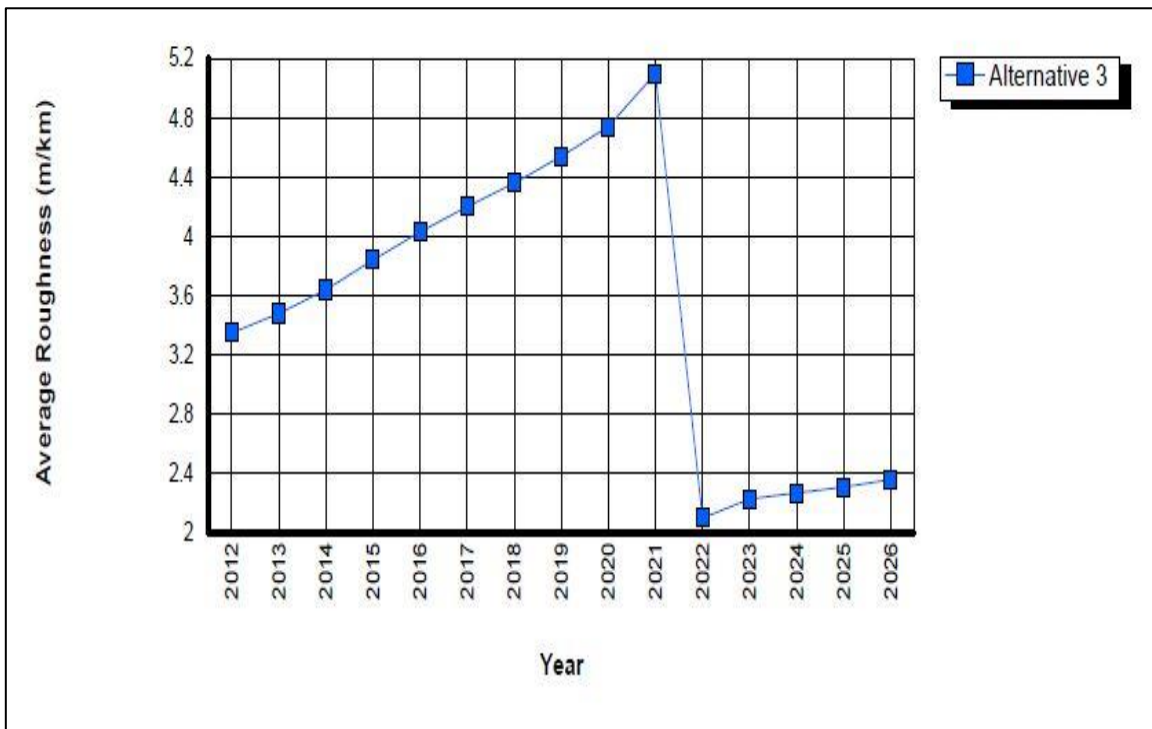


Figure 4.25 Roughness Progression for (R8) Road Section

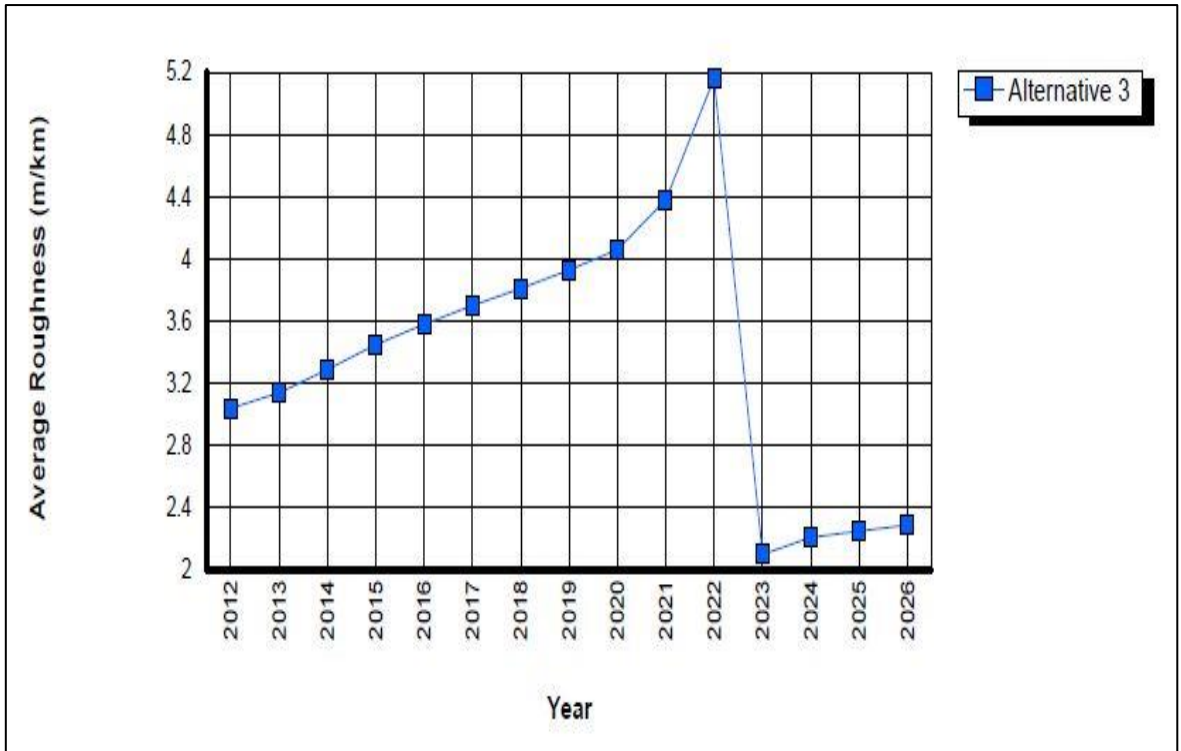


Figure 4.26 Roughness Progression for (R9) Road Section

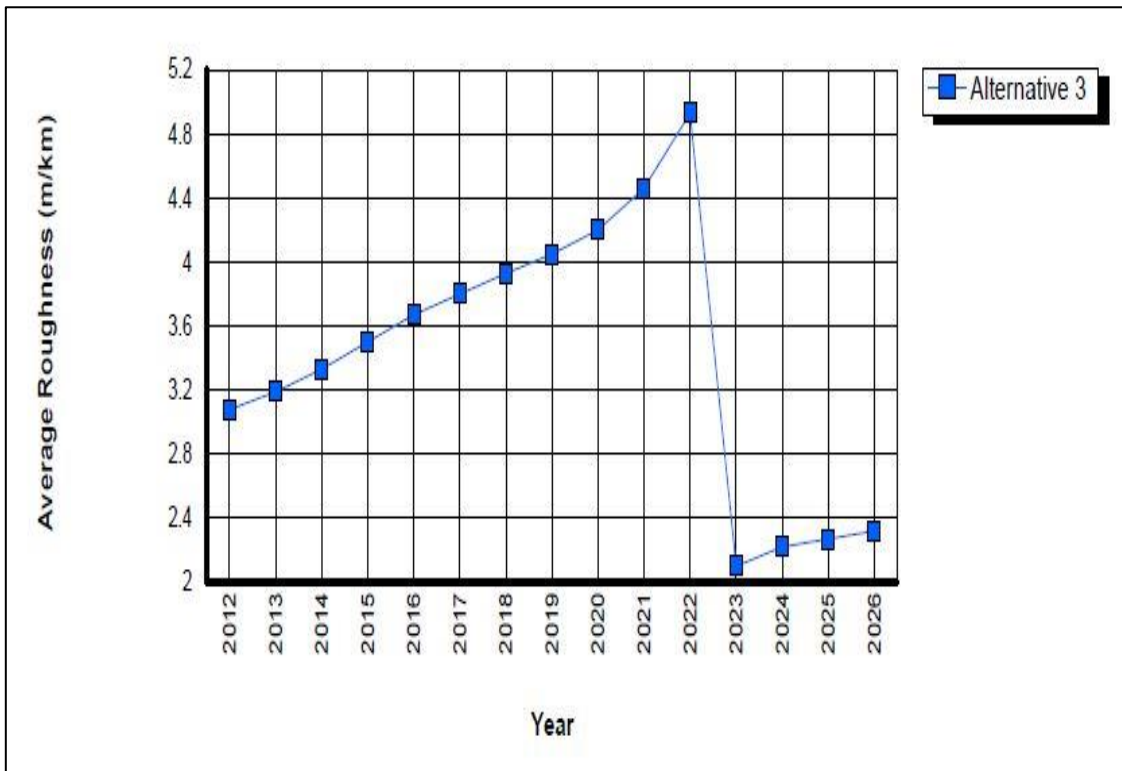


Figure 4.27 Roughness Progression for (R10) Road Section

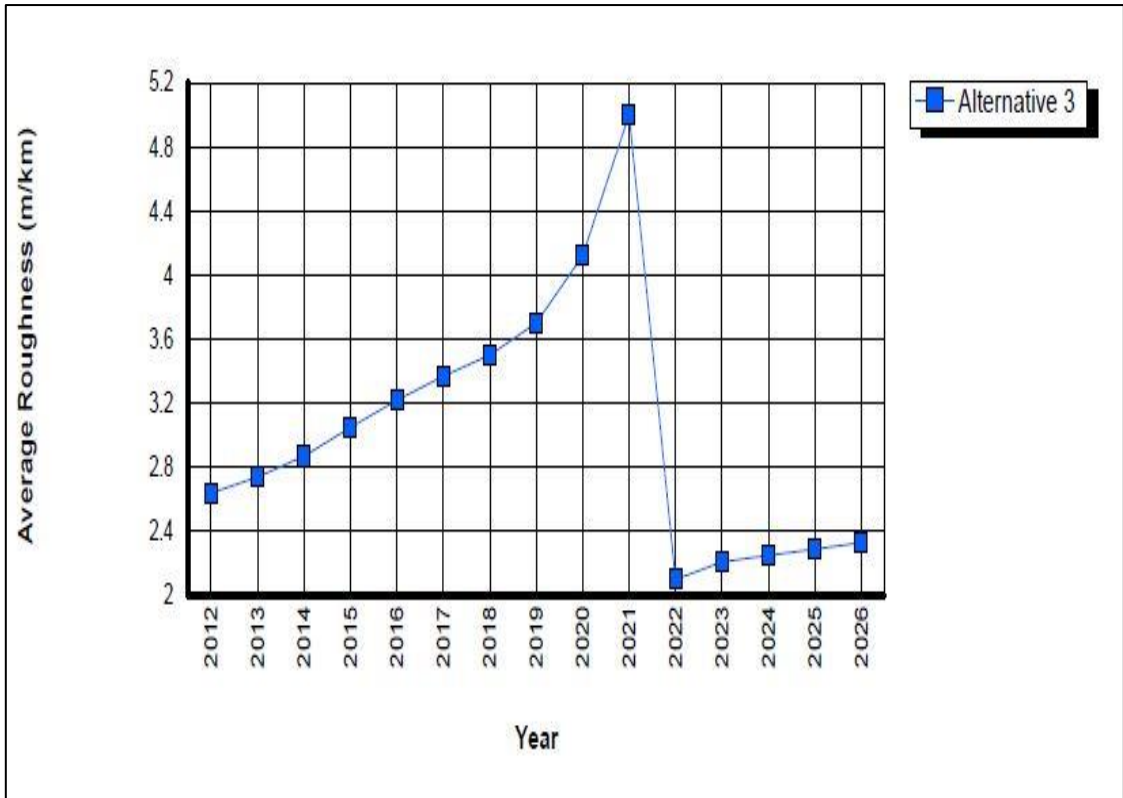


Figure 4.28 Roughness Progression for (R11) Road Section

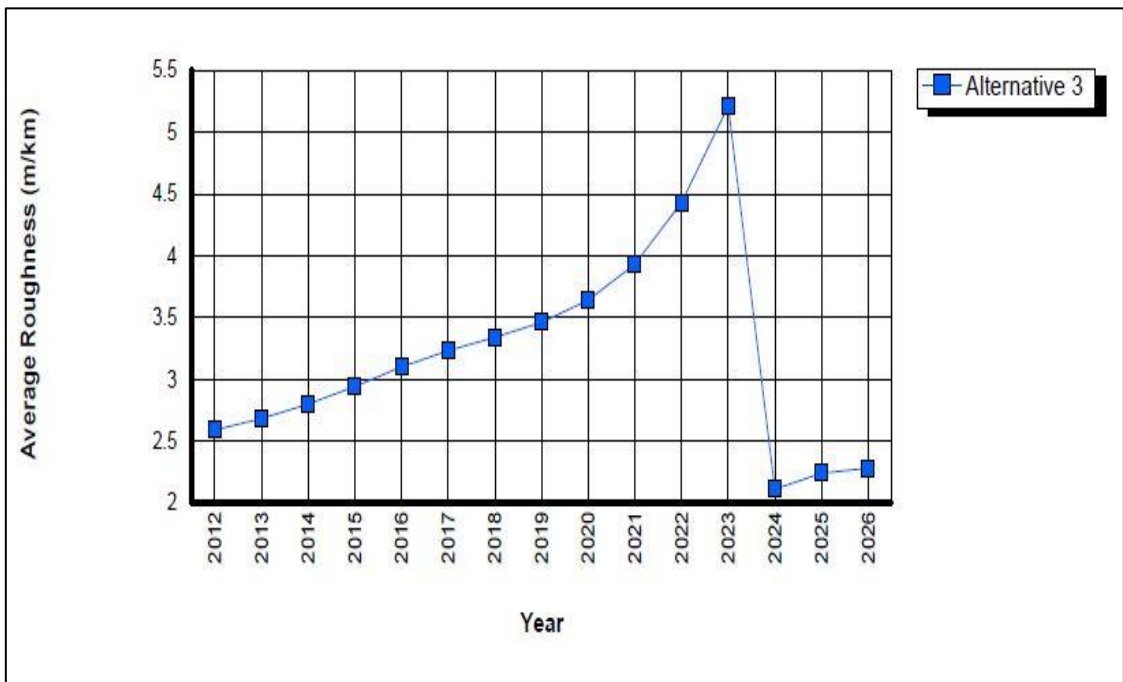


Figure 4.29 Roughness Progression for (R12) Road Section

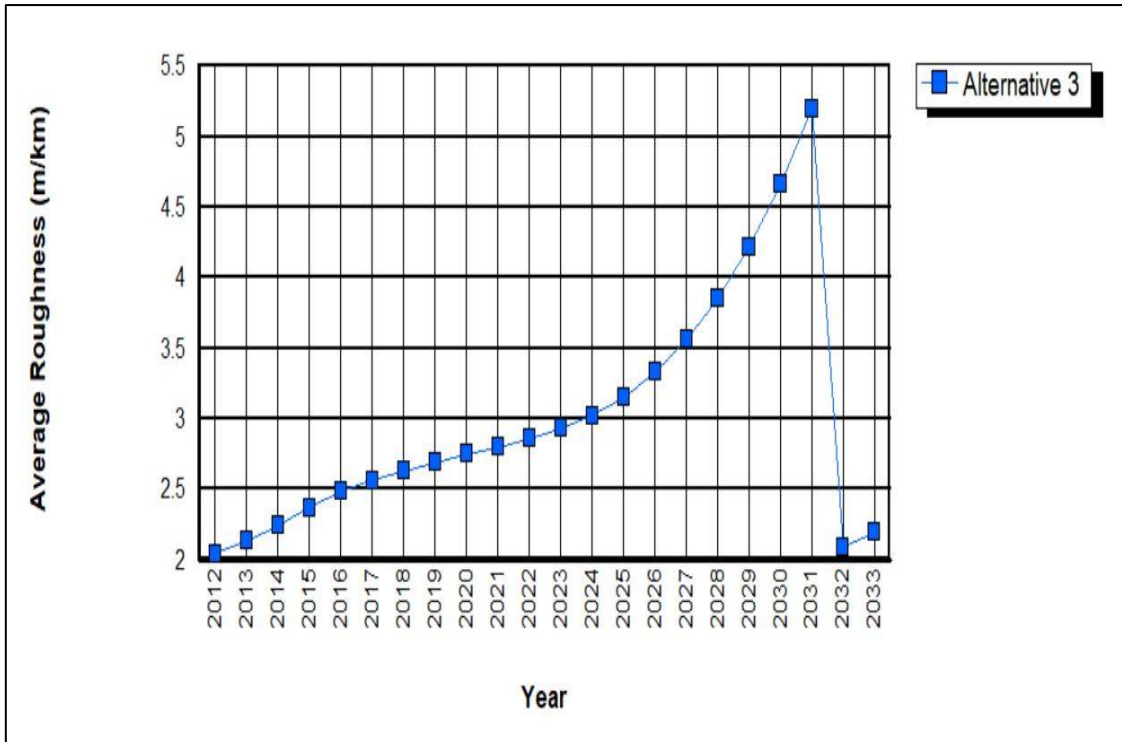


Figure 4.30 Roughness Progression for (R13) Road Section

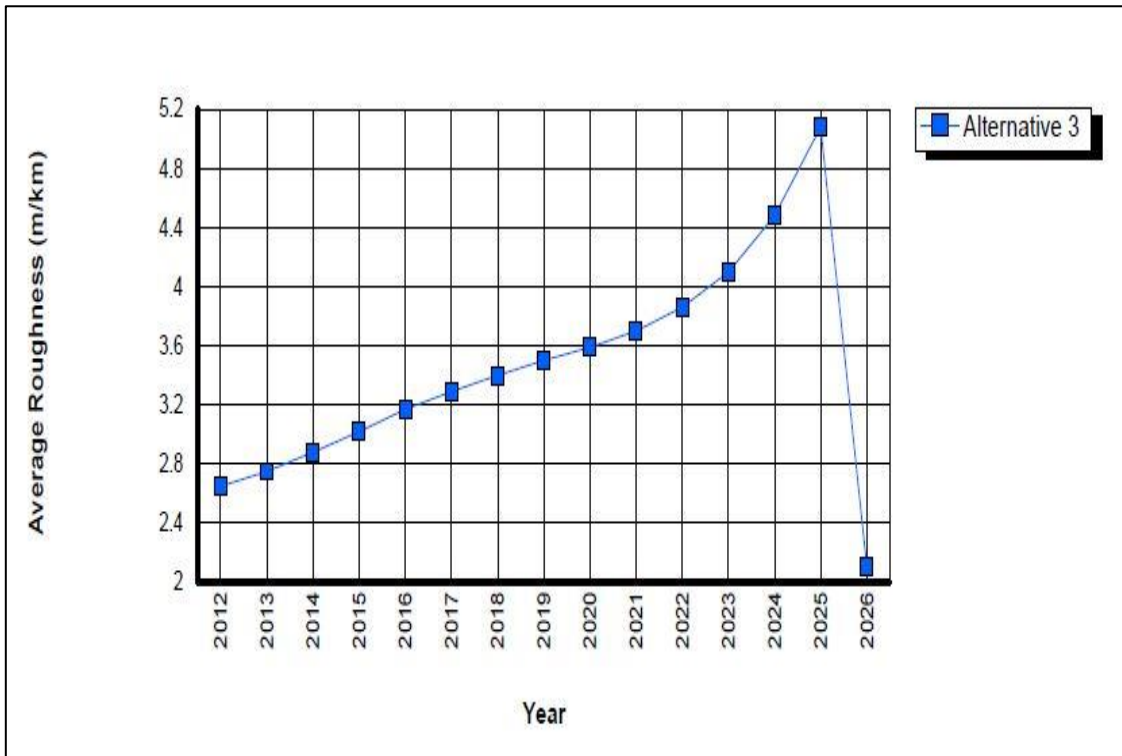


Figure 4.31 Roughness Progression for (R14) Road Section

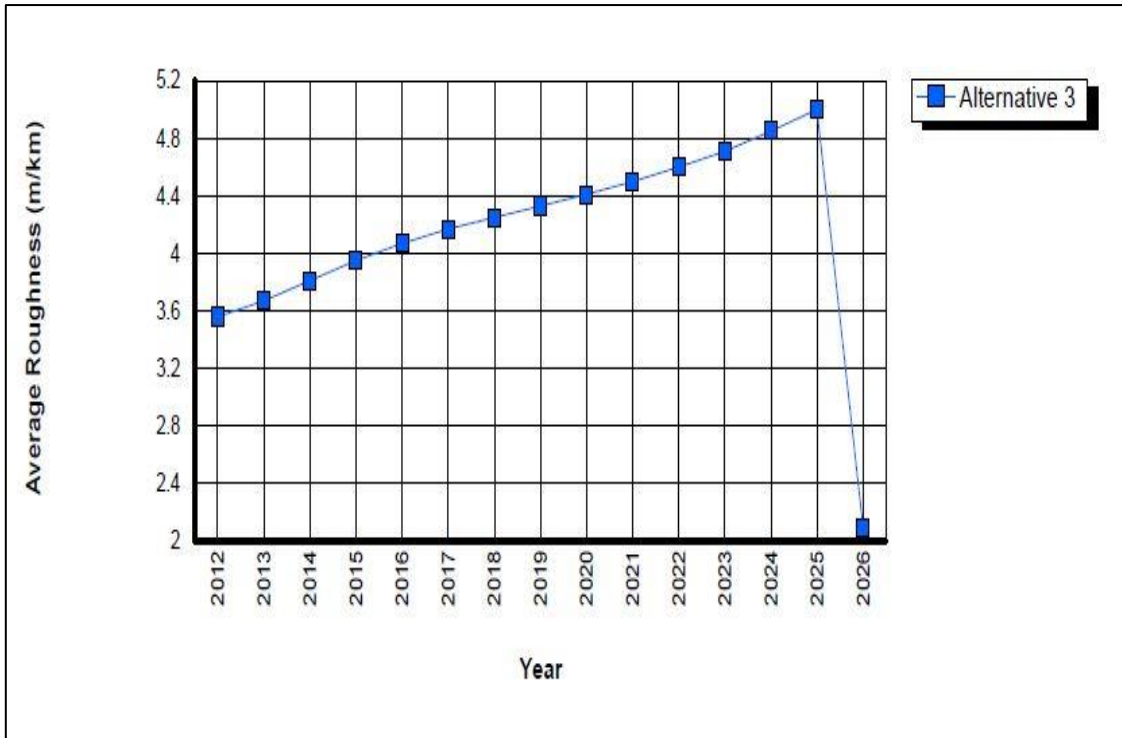


Figure 4.32 Roughness Progression for (R15) Road Section

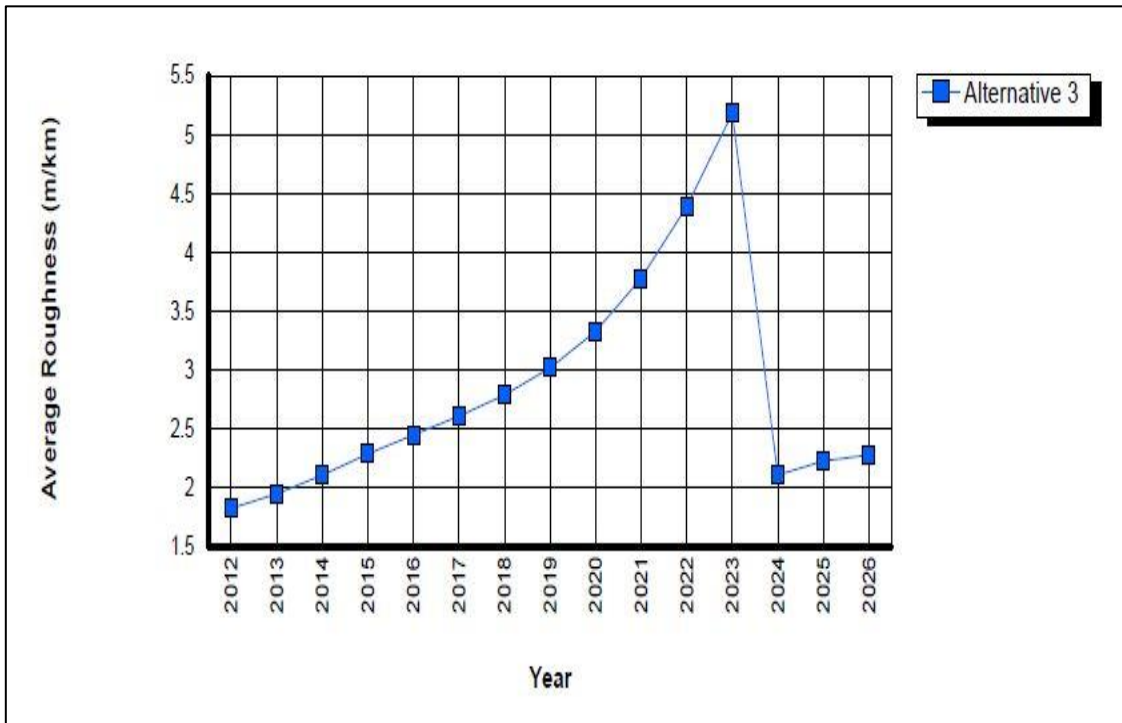


Figure 4.33 Roughness Progression for (R16) Road Section

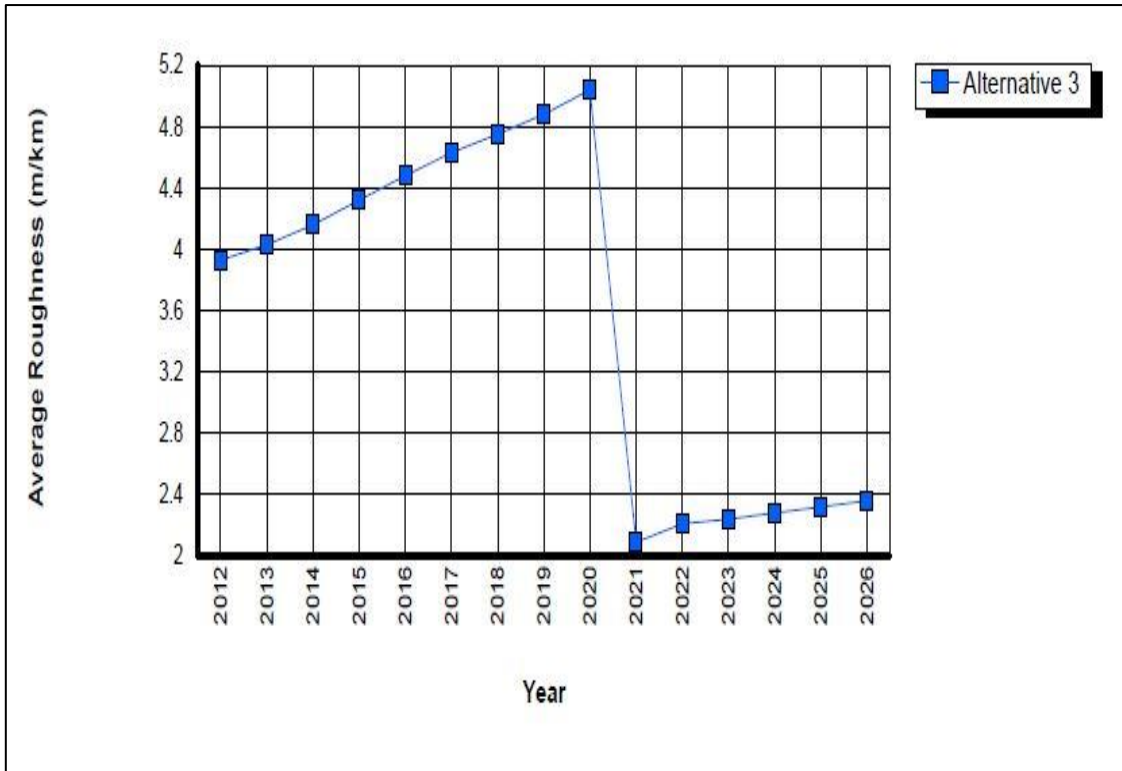


Figure 4.34 Roughness Progression for (R17) Road Section

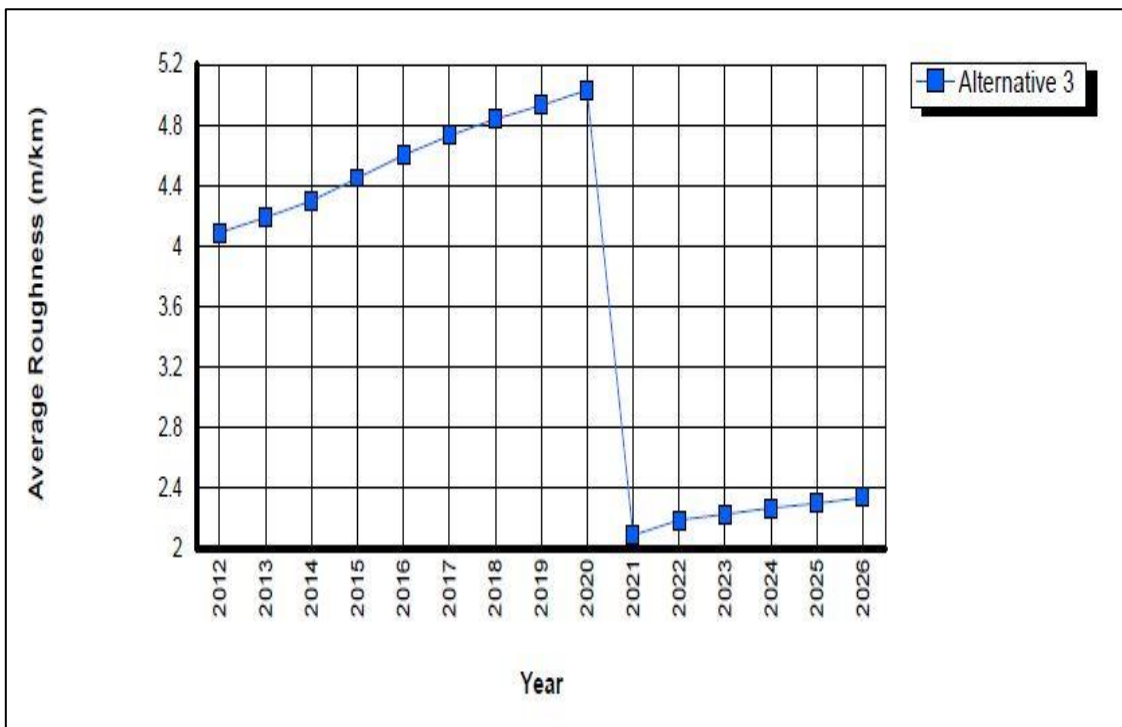


Figure 4.35 Roughness Progression for (R18) Road Section

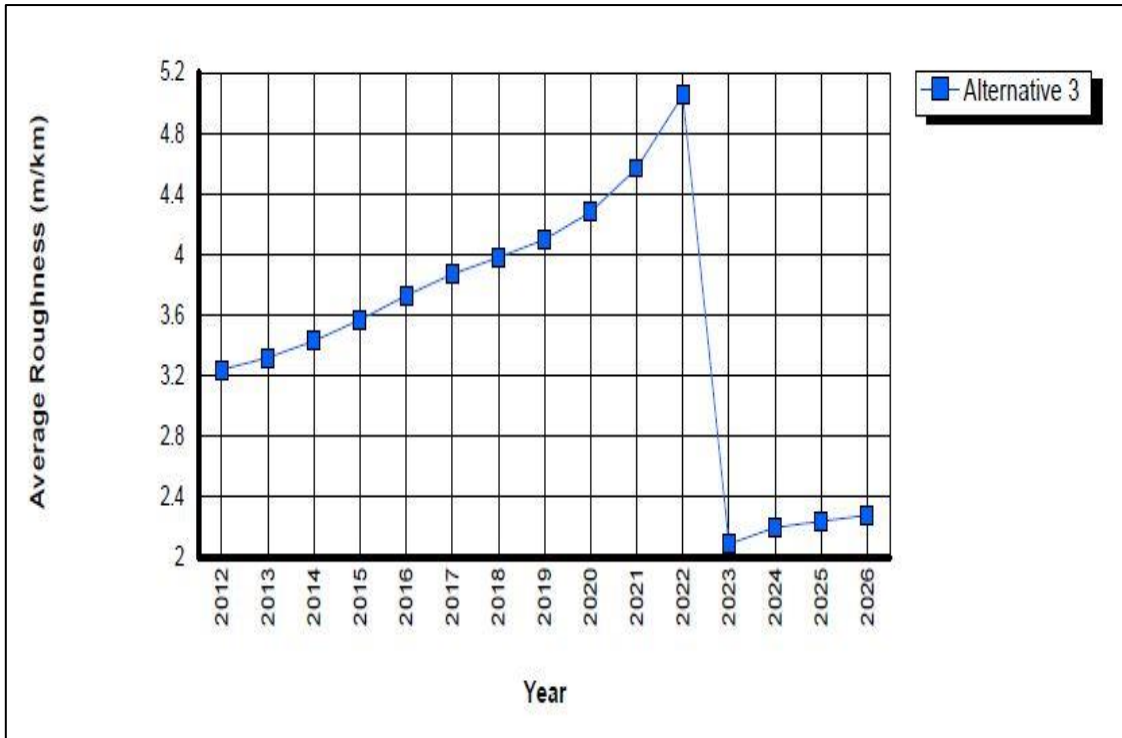


Figure 4.36 Roughness Progression for (R19) Road Section

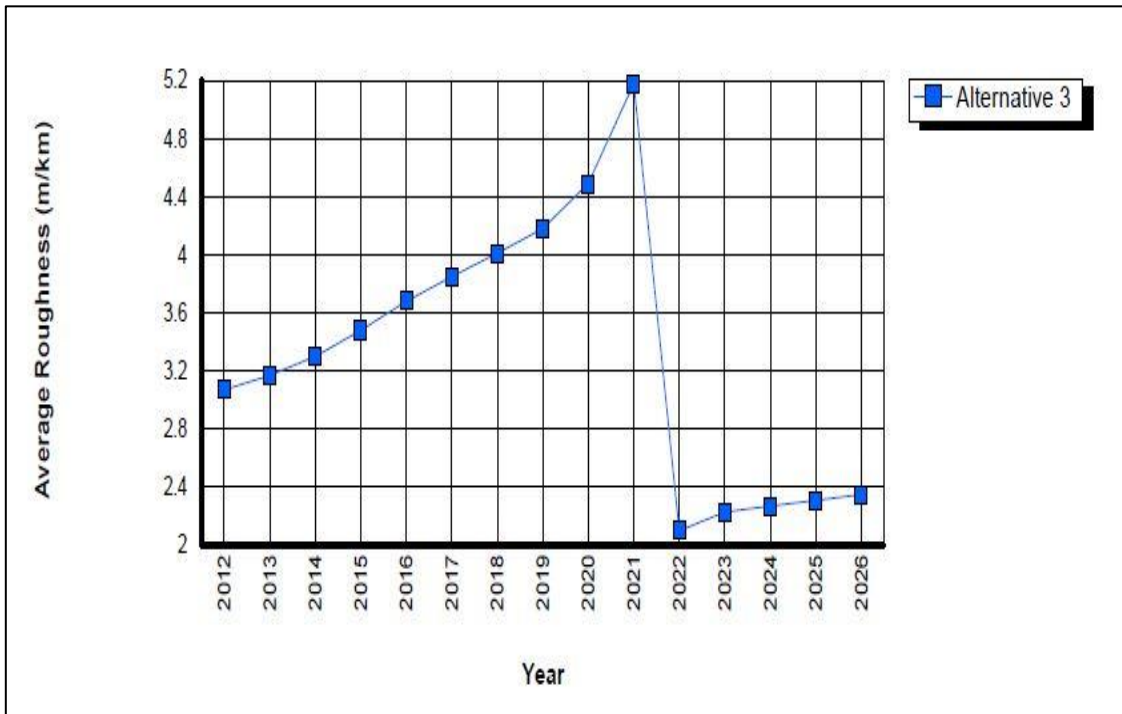


Figure 4.37 Roughness Progression for (R20) Road Section

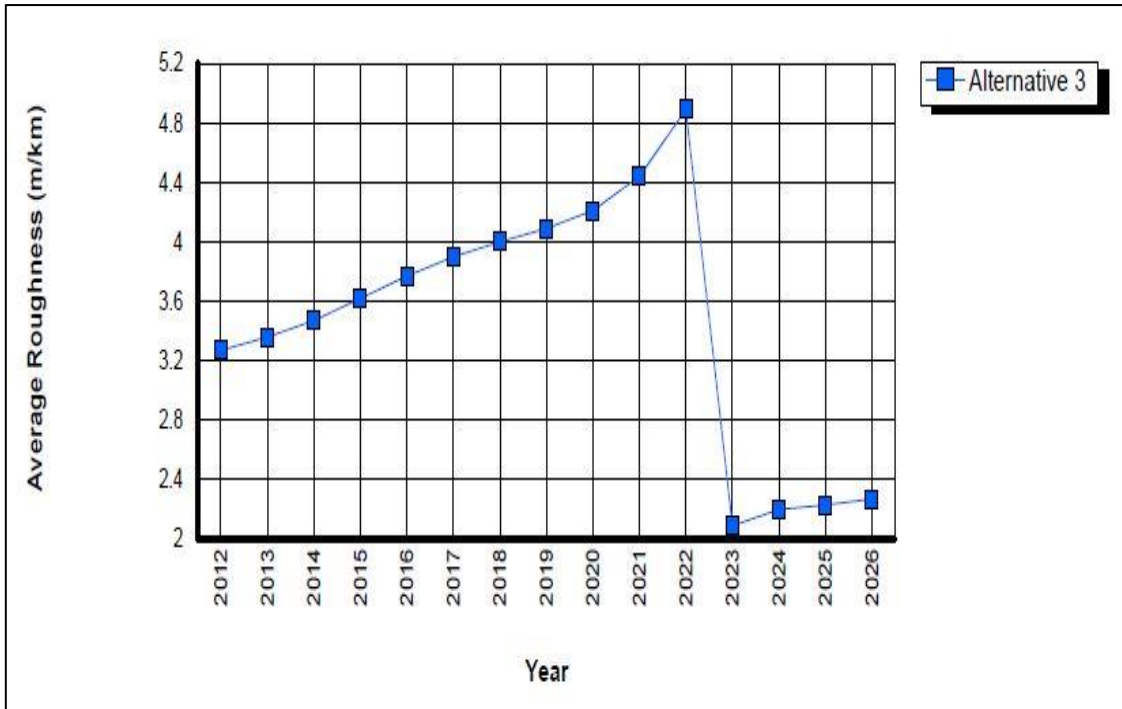


Figure 4.38 Roughness Progression for (R21) Road Section

Table 4.4 Remaining Service Life in Years

Section	RSL(Years)	Section	RSL(Years)
R1	6	R12	11
R2	6	R13	14
R3	8	R14	13
R4	8	R15	13
R5	5	R16	11
R6	5	R17	8
R7	12	R18	8
R8	9	R19	10
R9	10	R20	9
R10	10	R21	10
R11	9		

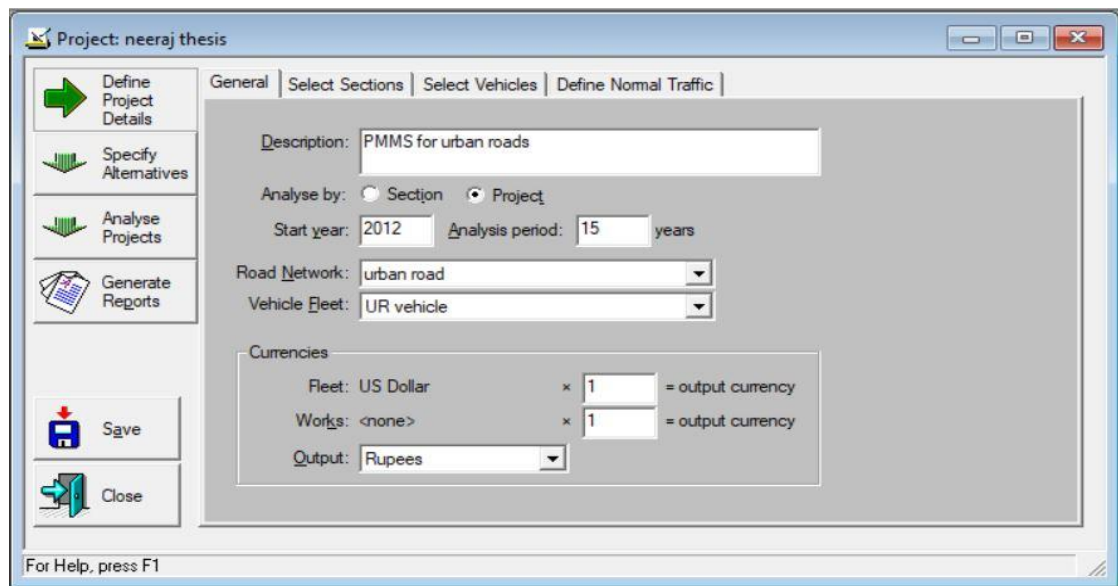
So, from the table 4.4, it has been observed that average RSL is approx. 9 years. RSL can be decisive factor in deciding the preference in M&R of road sections.

4.6 M&R STRATEGY FOR ALL ROAD SECTIONS

The Rehabilitation and Maintenance strategy in HDM-IV has been done for all the twenty-one road sections. The importance of this objective is to evaluate the distresses for the coming years and assign different M&R alternatives.

4.6.1 Input Data

The project has been created which consists of 'Urban road' and 'UR vehicle' as input. Analysis period (Intervention period) has been taken as 15 years. Analysis by section has been done.



The screenshot shows a software window titled 'Project: neeraj thesis' with a menu bar containing 'General', 'Select Sections', 'Select Vehicles', and 'Define Normal Traffic'. The 'General' tab is active, displaying the following input fields:

- Description: PMMS for urban roads
- Analyse by: Section Project
- Start year: 2012 Analysis period: 15 years
- Road Network: urban road (dropdown)
- Vehicle Fleet: UR vehicle (dropdown)
- Currencies section:
 - Fleet: US Dollar × 1 = output currency
 - Works: <none> × 1 = output currency
 - Output: Rupees (dropdown)

On the left side, there is a vertical toolbar with icons for 'Define Project Details', 'Specify Alternatives', 'Analyse Projects', 'Generate Reports', 'Save', and 'Close'. At the bottom left, it says 'For Help, press F1'.

Figure 4.39 Data Input for Project Analysis

4.6.2 Selection of road sections and vehicles

All the twenty-one road sections have been selected for the analysis. All the vehicles have been marked and selected from 'UR vehicle' Vehicle Fleet for the analysis of the project.

4.6.3 Definition of Normal Traffic

All the motorised vehicles have been input for all the sections individually with varying compositions. The average annual growth rate has been considered.

4.6.4 Proposed M & R Alternatives

There have been four alternatives proposed with various interventions (Table 4.5) keeping Level of Serviceability (LOS) [chapter 3] in the mind. The ‘Base Alternative’ has been used as a scheduled alternative with periodic interventions. The proposed M&R Alternatives has been mentioned in the table 5.5

Table 4.5 Used M& R Alternatives

M&R Strategy	Work standards	Description of work	Intervention Level
Base Alternative	Routine	Crack Sealing	schedule annually
		Patching	schedule annually
Alternative 1	Resealing + Thin Overlay	provide 25 mm DBSD	Total damage area $\geq 8\%$ of the total area
		provide 25 mm BC	Roughness $\geq 2.5, \leq 3.5$ IRI
Alternative 2	Thick Overlay	Provide 40 mm BC	Roughness $\geq 3.5, \leq 4.8$ IRI
Alternative 3	Reconstruction	Provide 75 mm DBM + 40 mm BC	Roughness ≥ 5 IRI

Total Damage Area comprises of cracked, Ravelled and Potholed area

4.6.5 M & R Alternative Specifications

The specifications of M&R alternatives have been done in in the project. With the required interventions that has kept LOS of road network in the desirable limits, the alternatives have been assigned to all the sections of the road network.

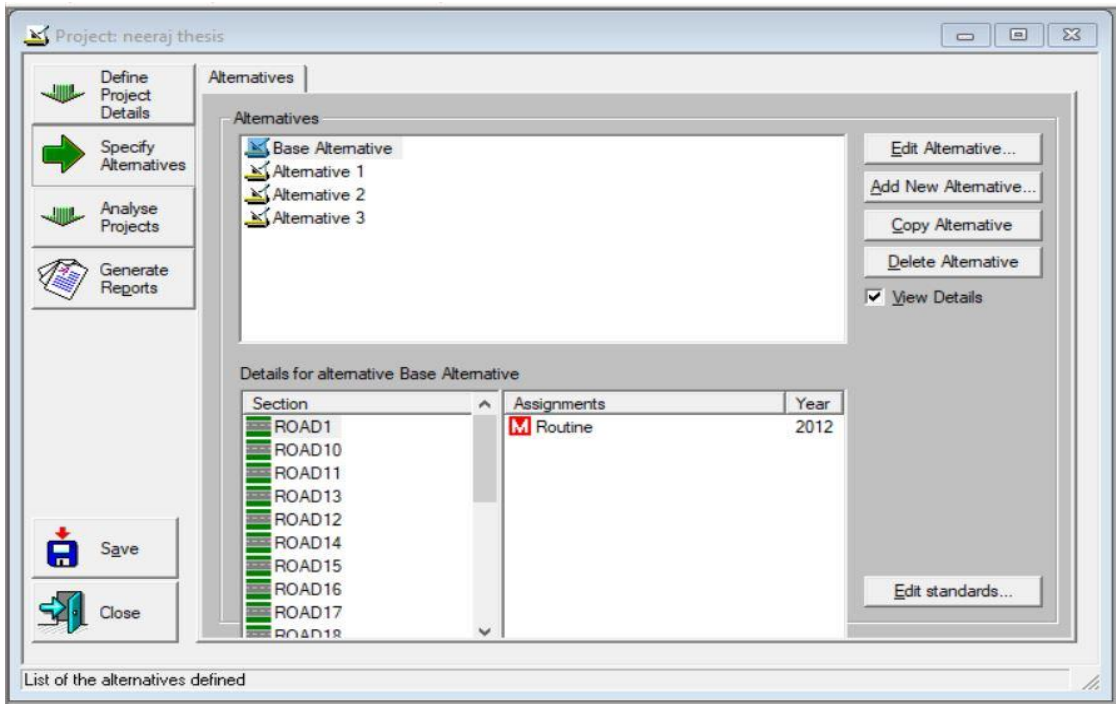


Figure 4.40 M&R Alternatives for Project Analysis

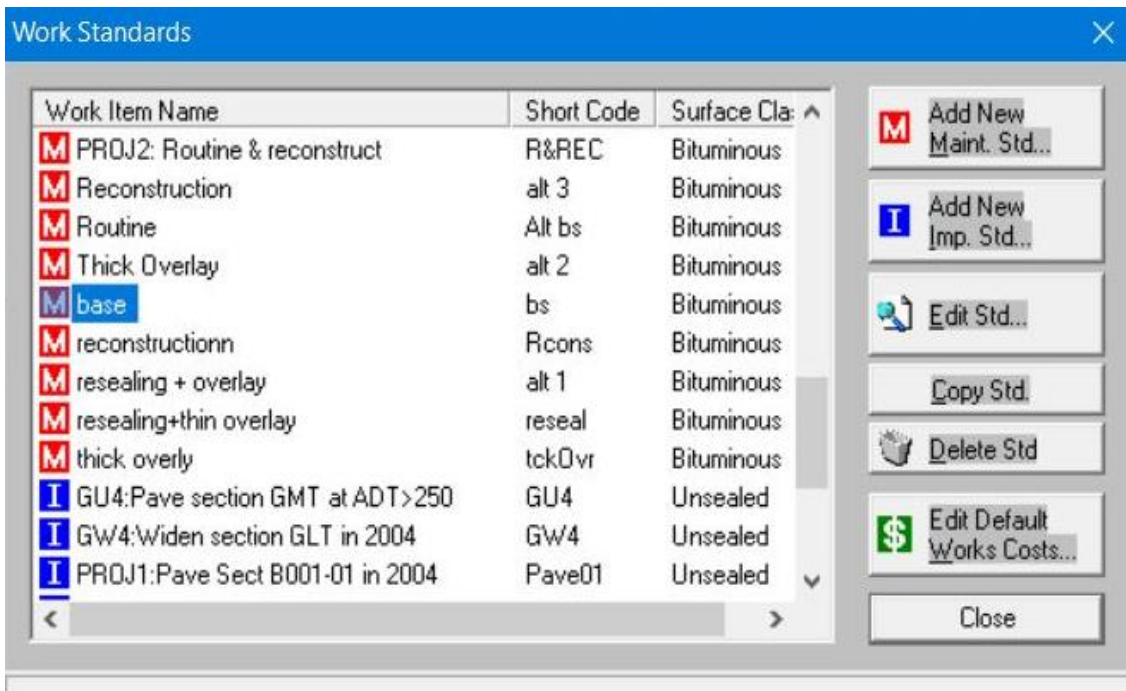


Figure 4.41 Definition of Work Standards

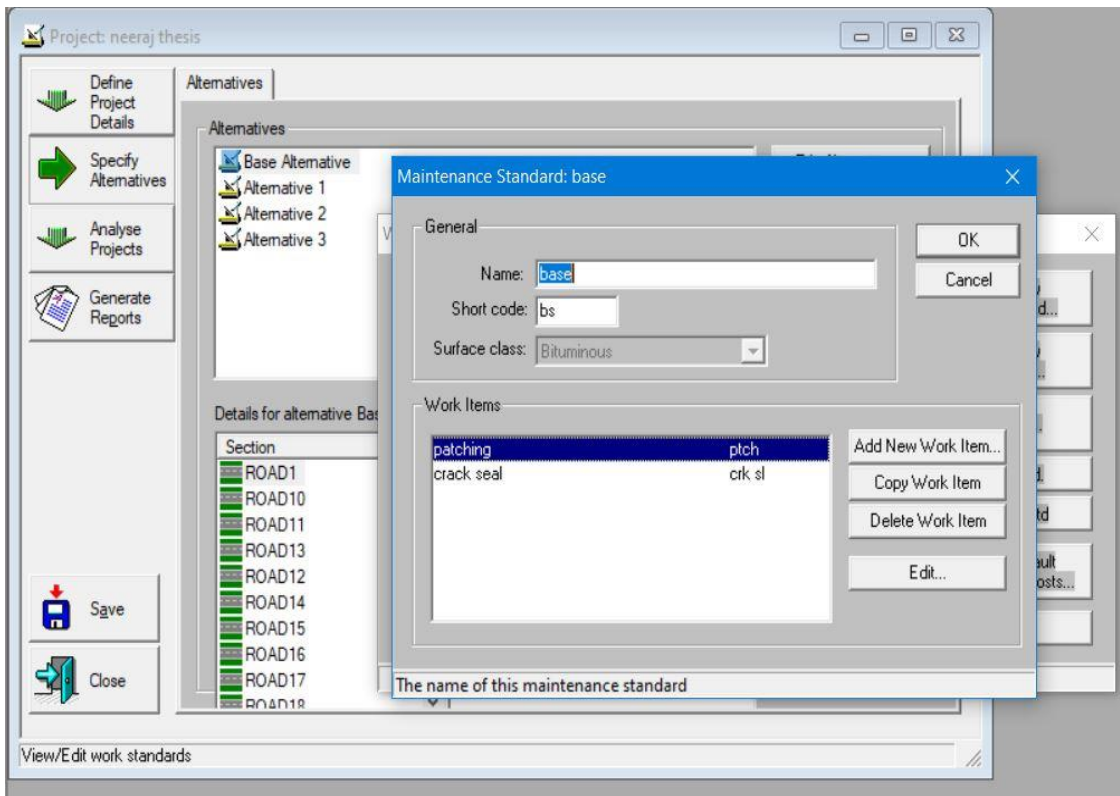


Figure 4.42 Definition of Base Alternative

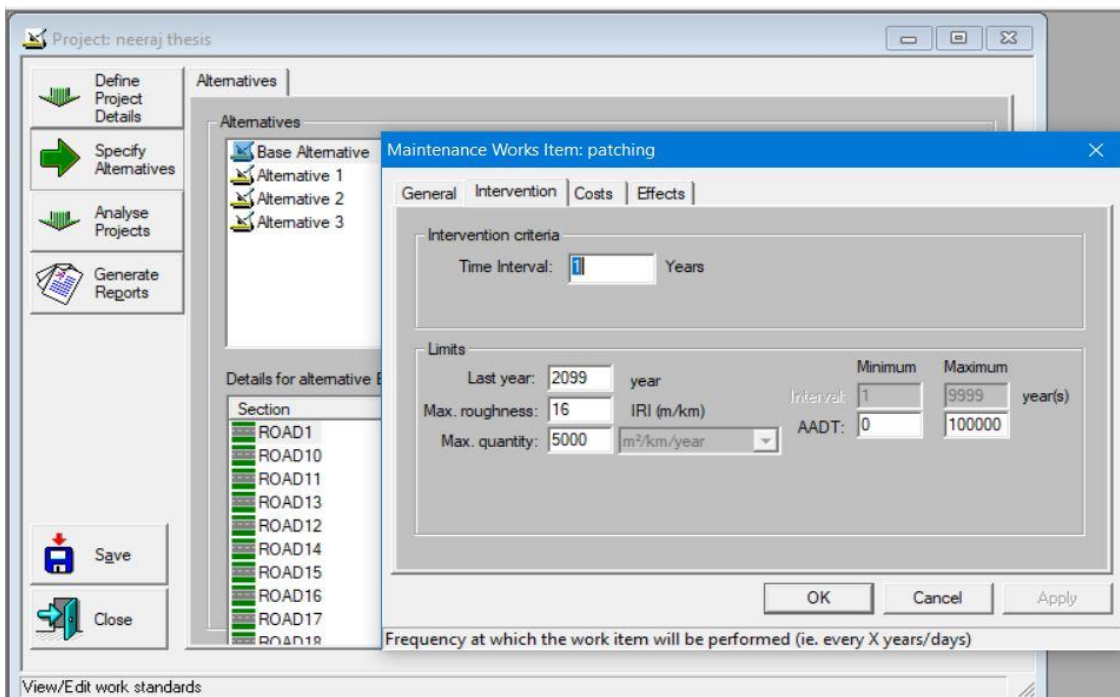


Figure 4.43 Periodic Interventions for Work Items

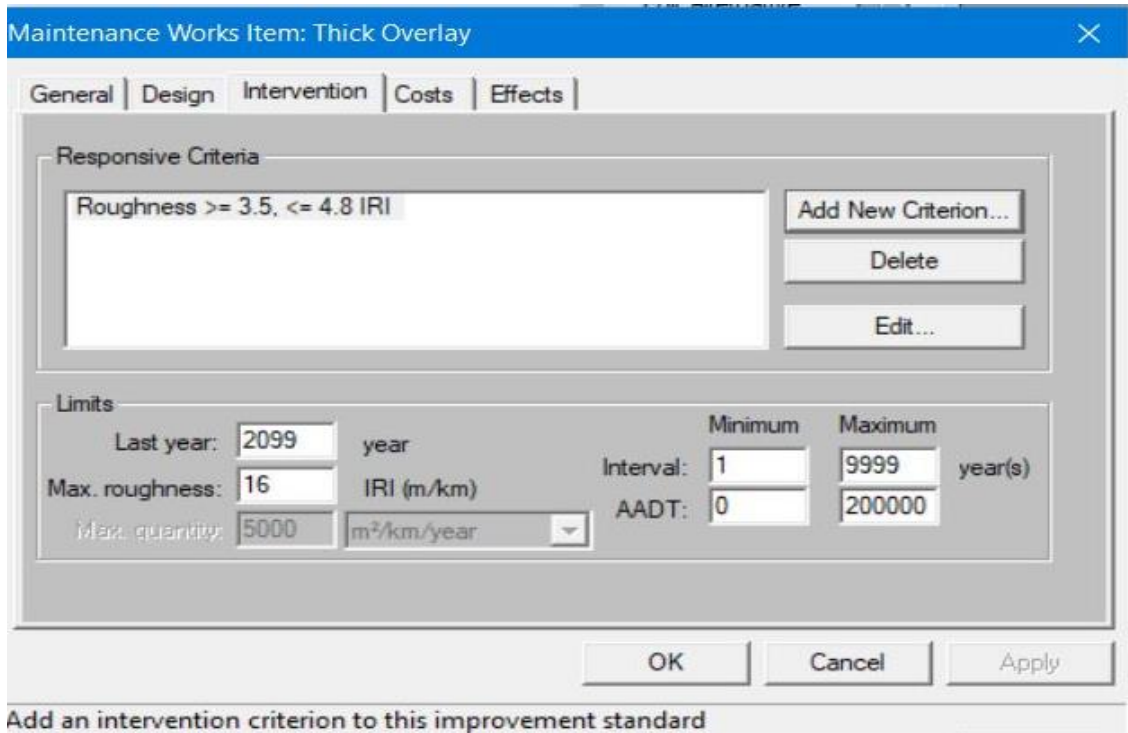


Figure 4.44 Responsive Interventions for Work Items

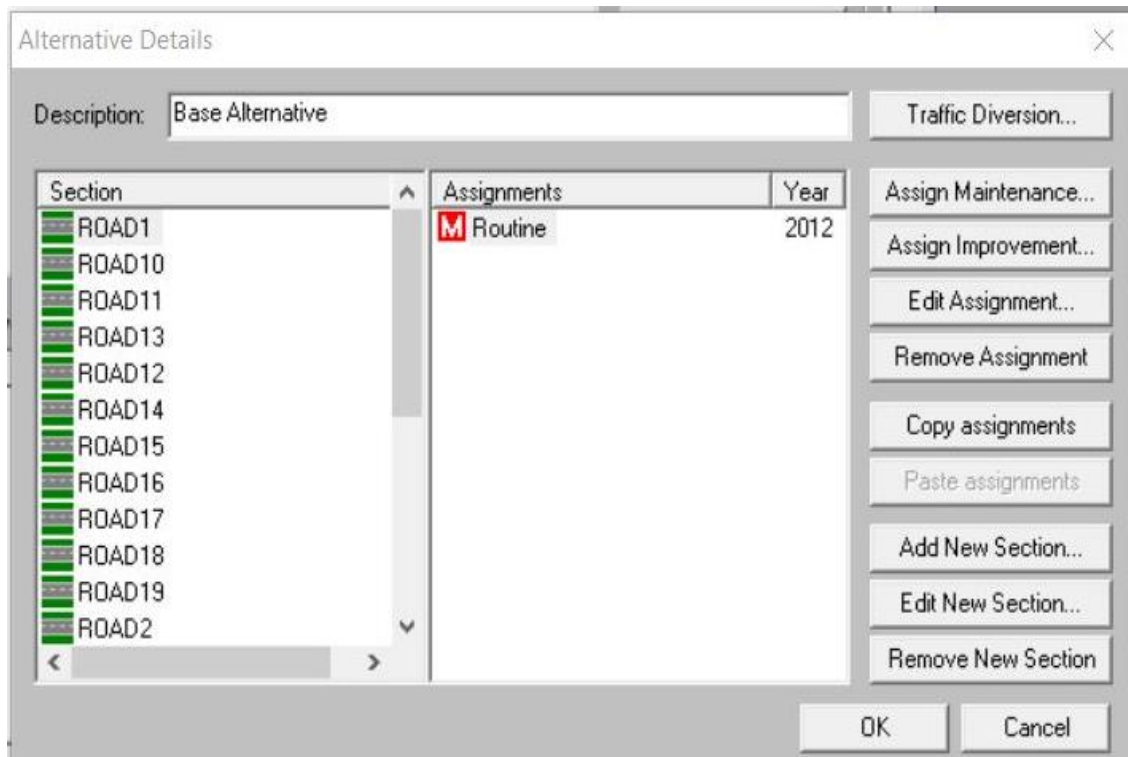


Figure 4.45 Alternative Details and Assignment

4.6.6 Project Analysis

The project analysis has been done for all the sections with 15 years analysis period for all vehicle types defined in vehicle fleet. All the 4 alternatives of M&R has been used for the project road network. The various deterioration and M&R work reports has been generated from the data defined above.

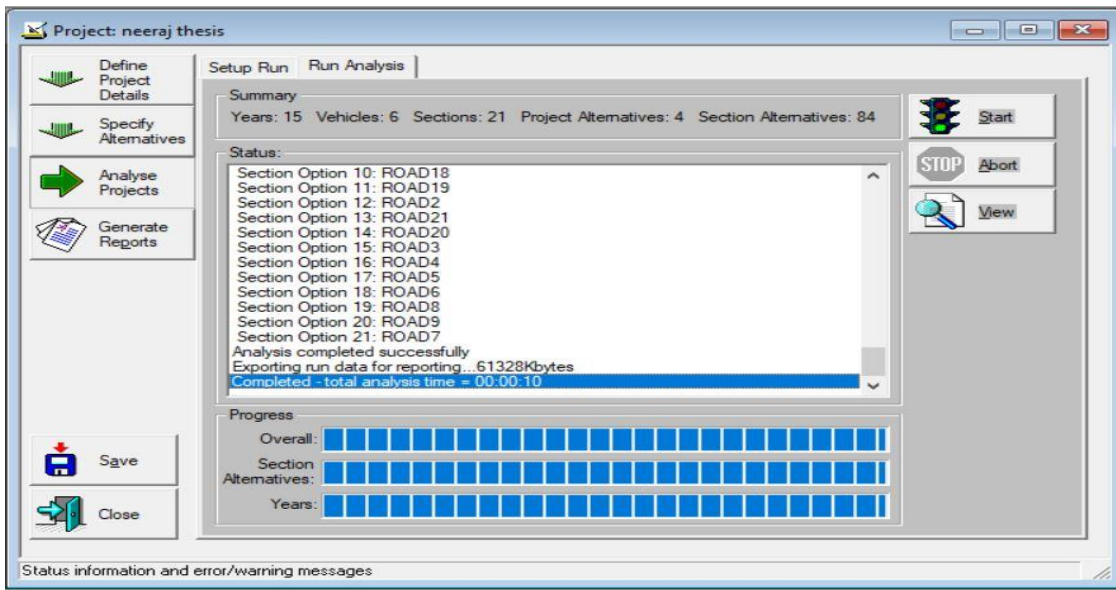


Figure 4.46 Completion of Project Analysis

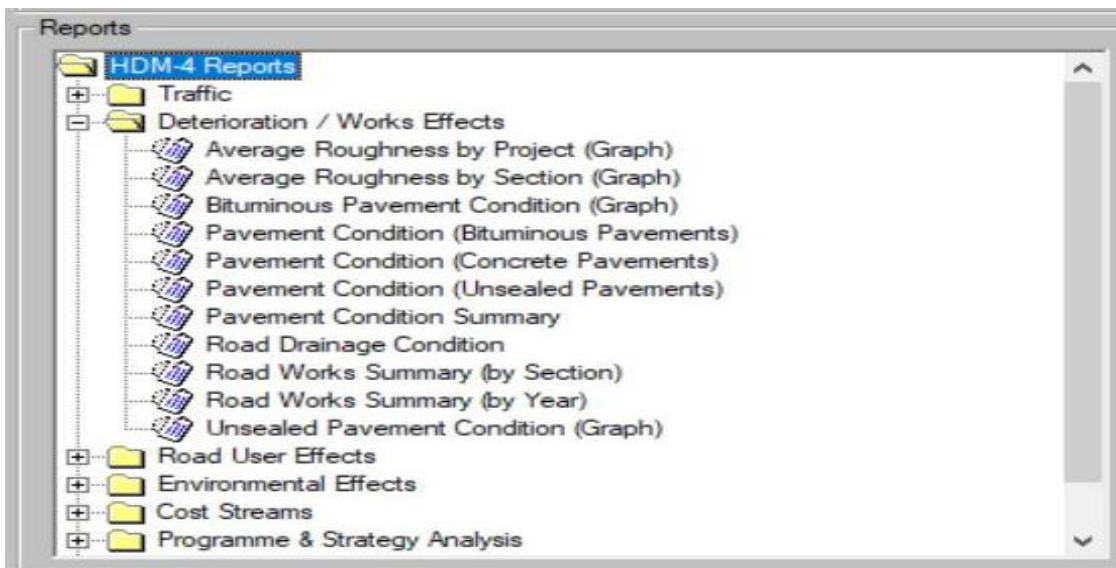


Figure 4.47 Reports Generated from Project Analysis

4.7 PAVEMENT PERFORMANCE PREDICTION

Average roughness per year of all the road sections with effect of all 4 Maintenance and Rehabilitation alternatives for the analysis period has been predicted with the HDM-IV modelling. Average roughness progression graphs can be a very reliable and worthy in accessing the pavement conditions since roughness is the distress which takes consideration of actual pavement condition. The graphs have been shown w.r.t. time. These graphs show how the interventions will trigger and what effect the interventions will have at a particular section after a particular period on average roughness and hence on the pavement condition.

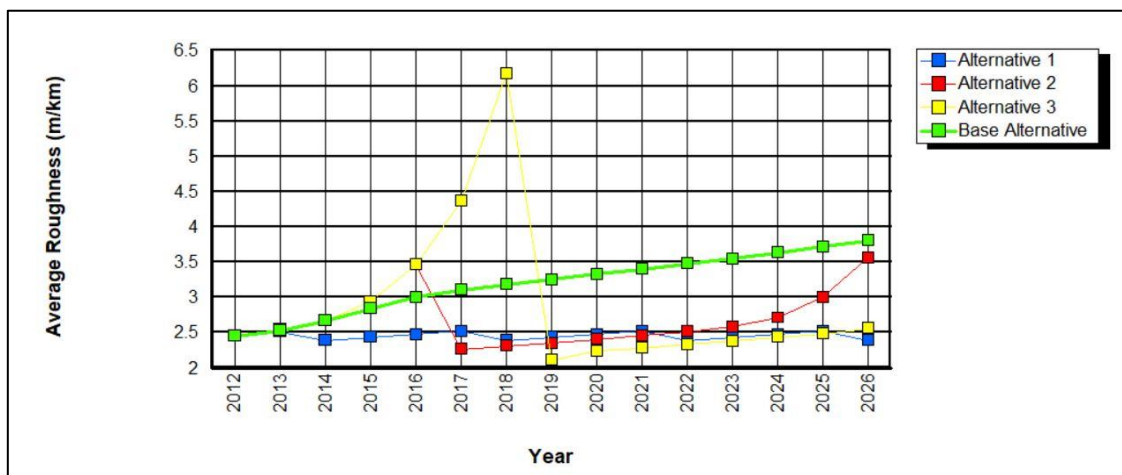


Figure 4.48 Average Roughness Progression under all alternatives for section R1

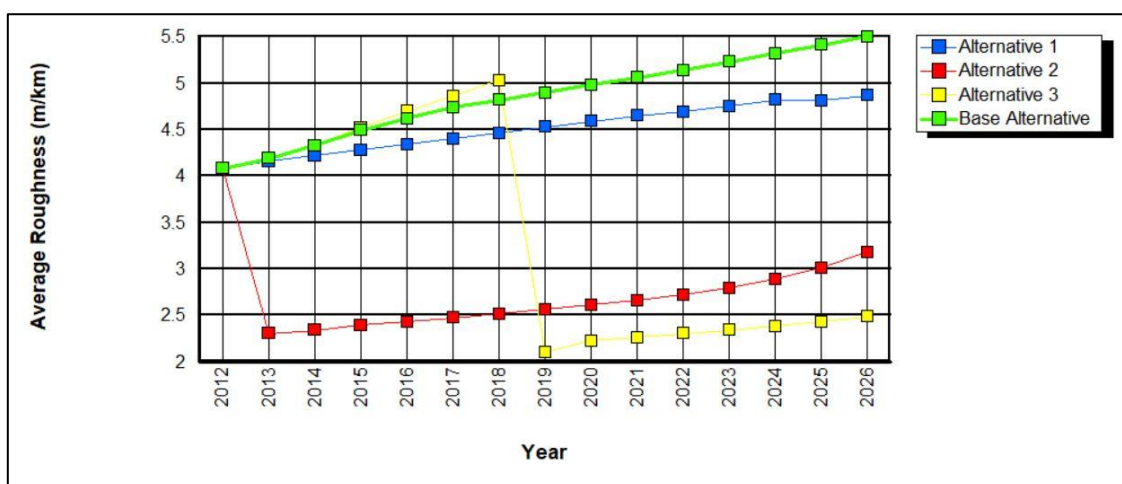


Figure 4.49 Average Roughness Progression under all alternatives for section R2

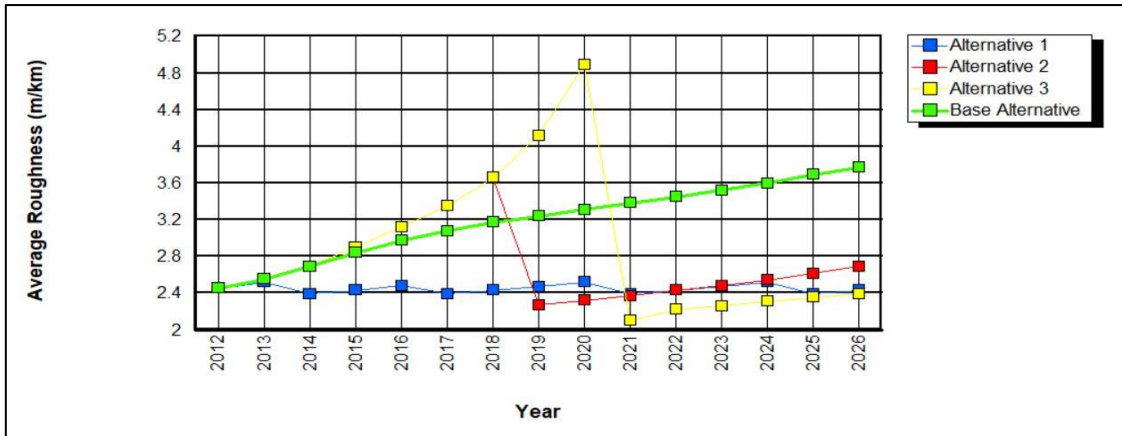


Figure 4.50 Average Roughness Progression under all alternatives for section R3

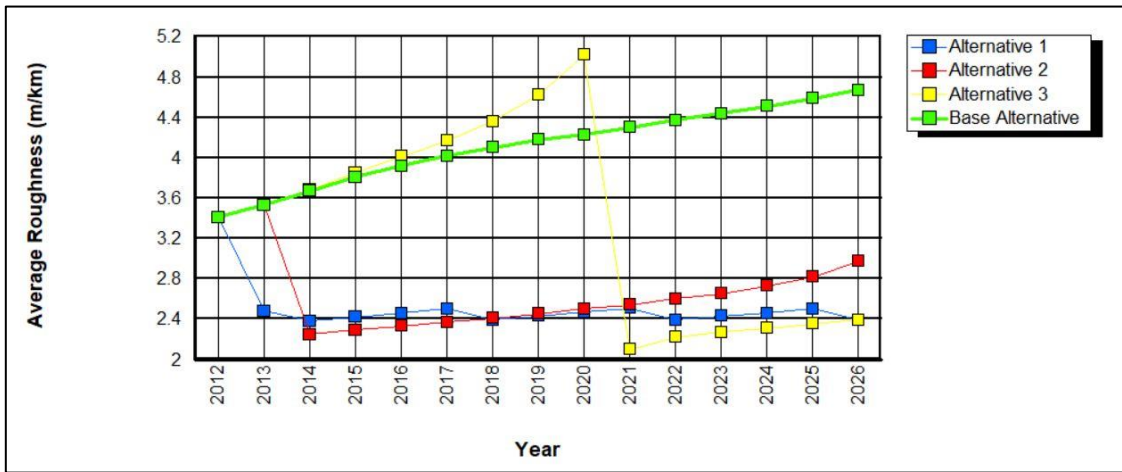


Figure 4.51 Average Roughness Progression under all alternatives for section R4

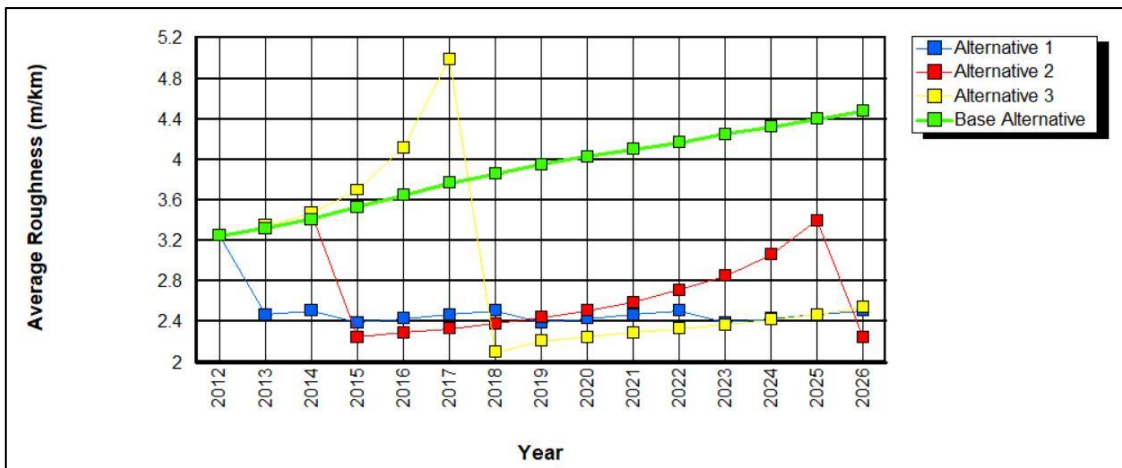


Figure 4.52 Average Roughness Progression under all alternatives for section R5

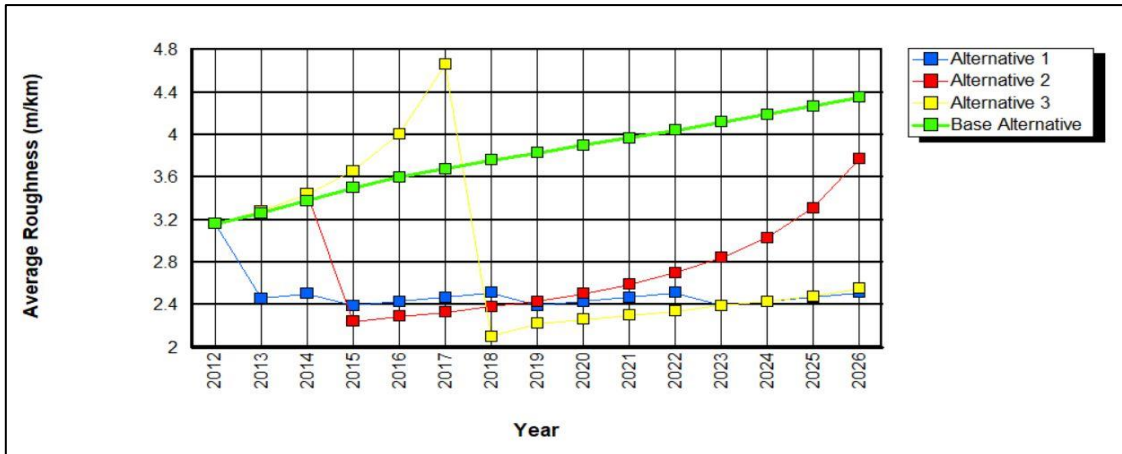


Figure 4.53 Average Roughness Progression under all alternatives for section R6

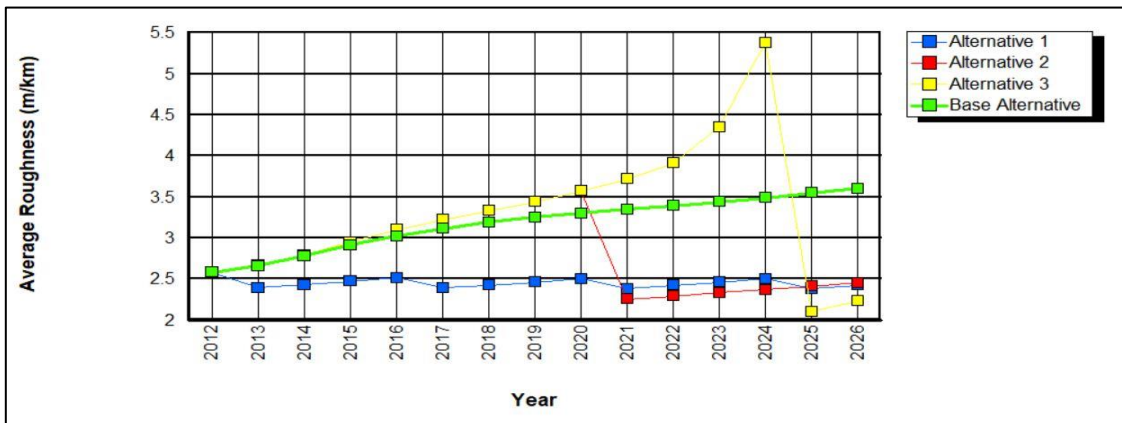


Figure 4.54 Average Roughness Progression under all alternatives for section R7

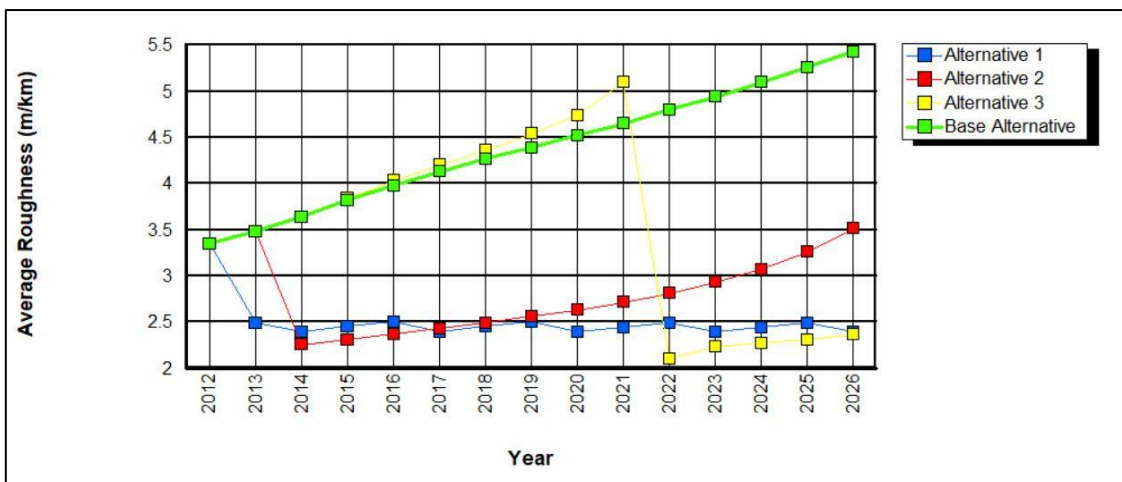


Figure 4.55 Average Roughness Progression under all alternatives for section R8

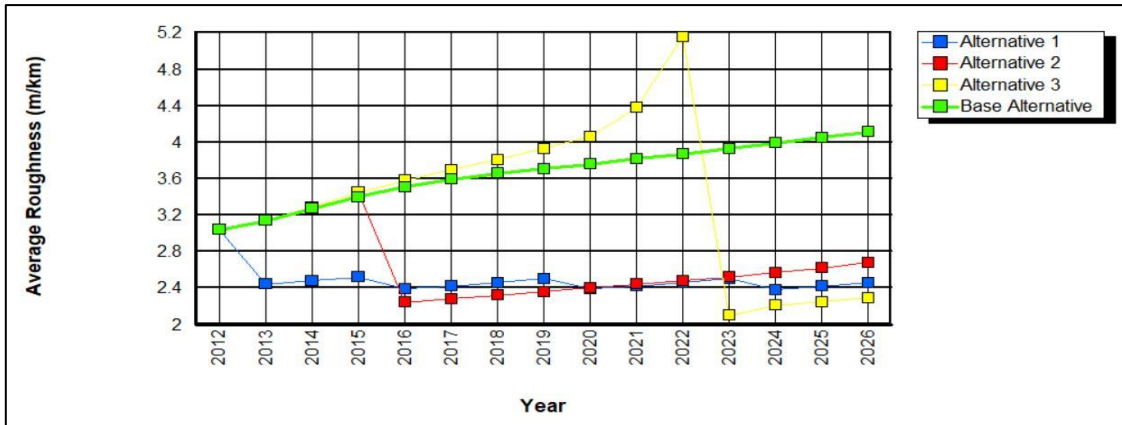


Figure 4.56 Average Roughness Progression under all alternatives for section R9

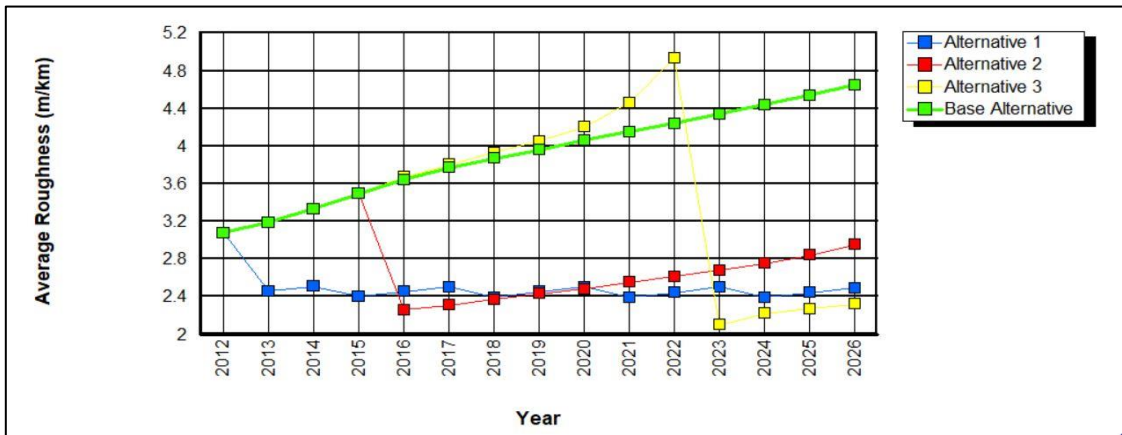


Figure 4.57 Average Roughness Progression under all alternatives for section R10

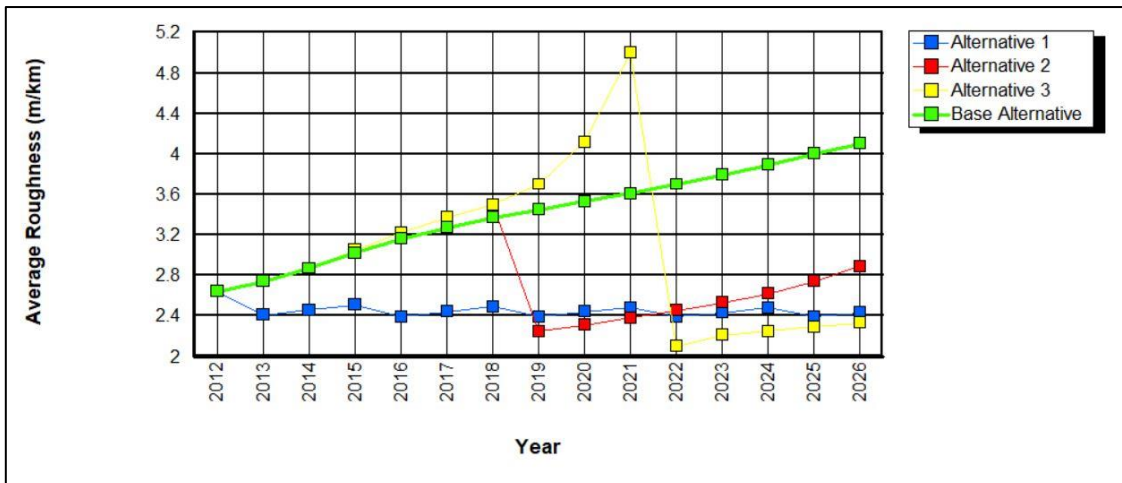


Figure 4.58 Average Roughness Progression under all alternatives for section R11

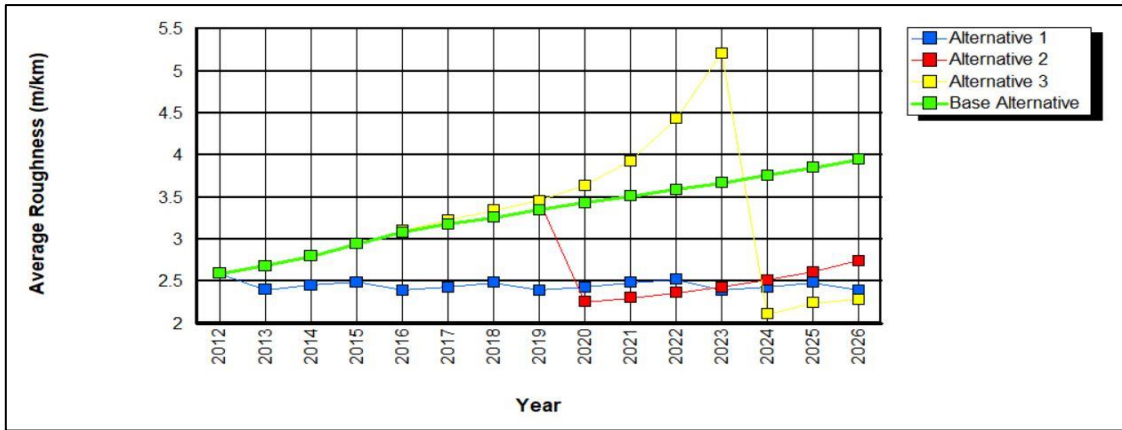


Figure 4.59 Average Roughness Progression under all alternatives for section R12

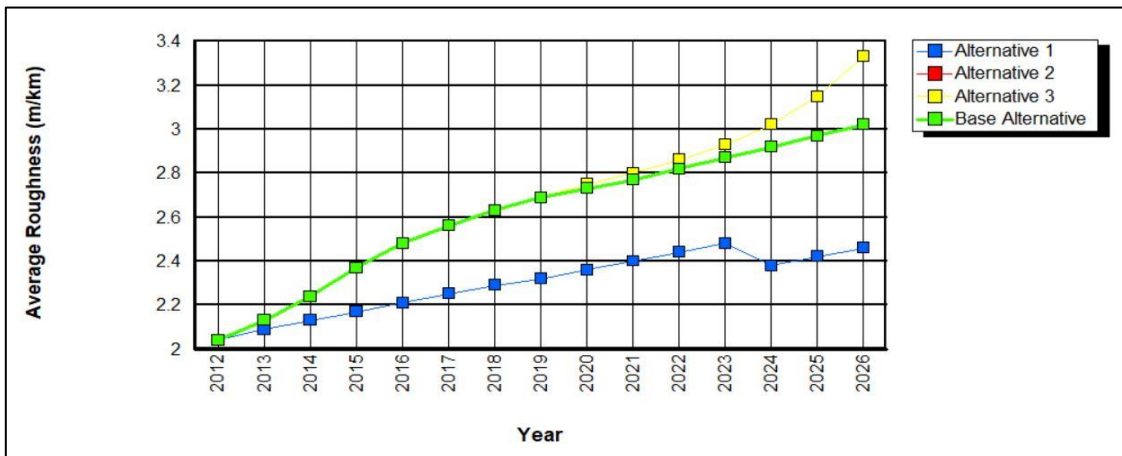


Figure 4.60 Average Roughness Progression under all alternatives for section R13

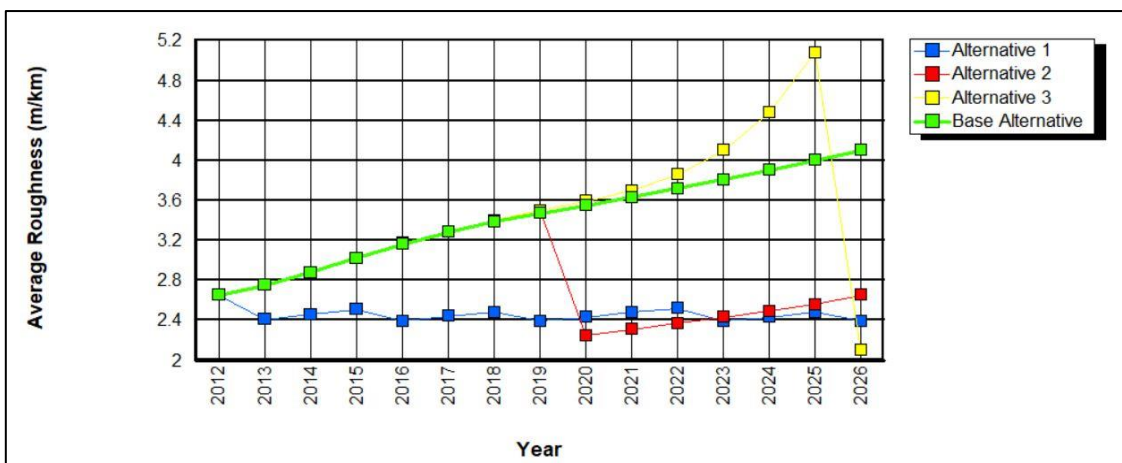


Figure 4.61 Average Roughness Progression under all alternatives for section R14

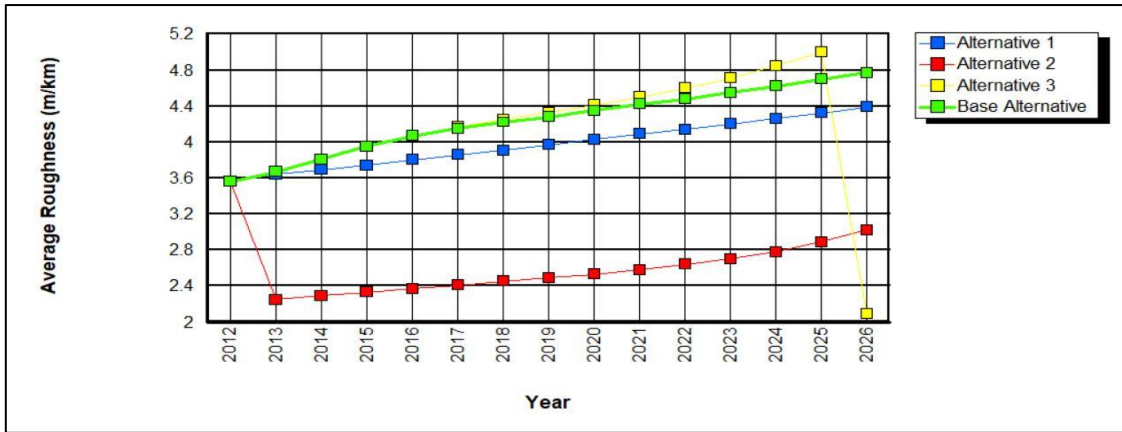


Figure 4.62 Average Roughness Progression under all alternatives for section R15

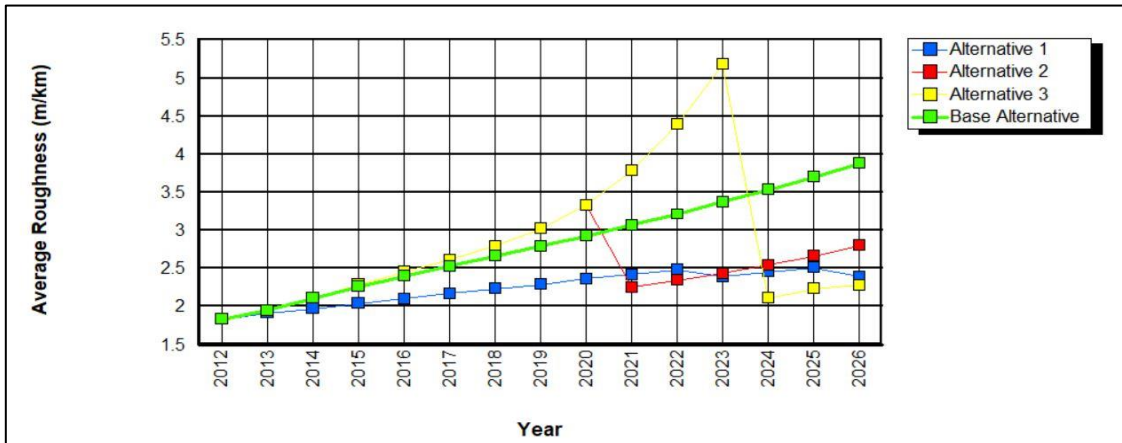


Figure 4.63 Average Roughness Progression under all alternatives for section R16

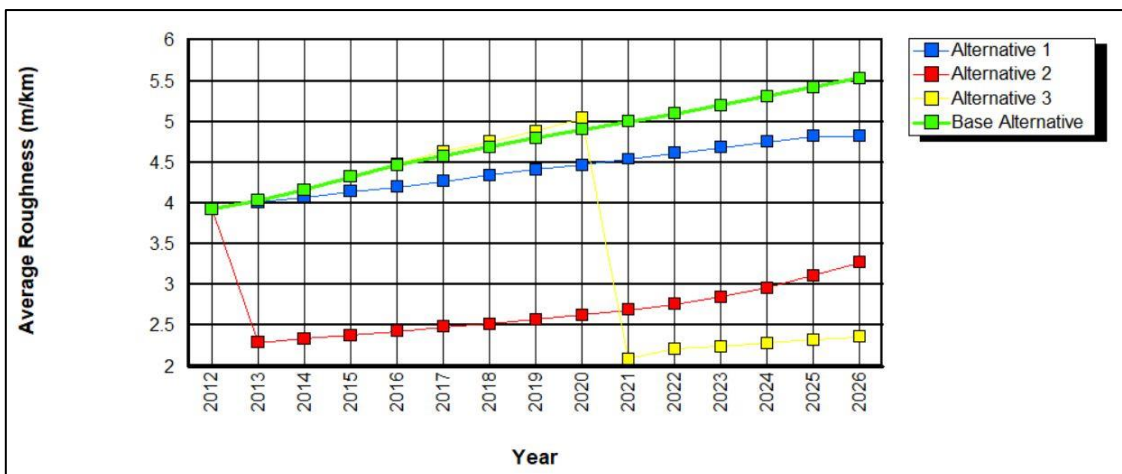


Figure 4.64 Average Roughness Progression under all alternatives for section R17

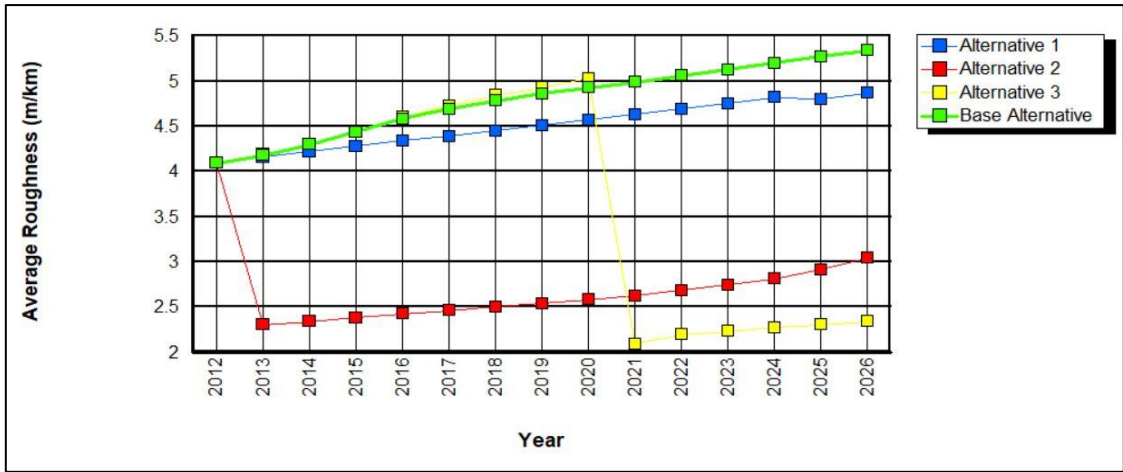


Figure 4.65 Average Roughness Progression under all alternatives for section R18

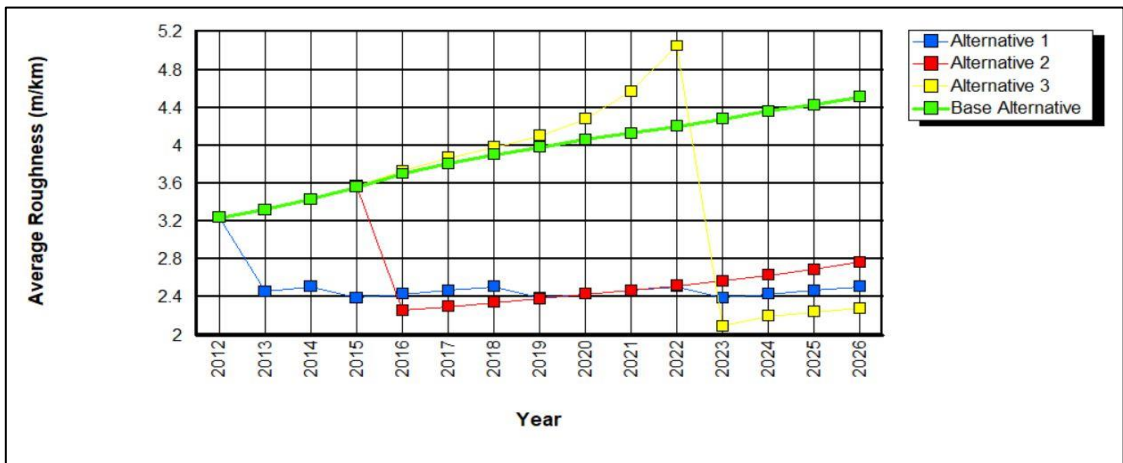


Figure 4.66 Average Roughness Progression under all alternatives for section R19

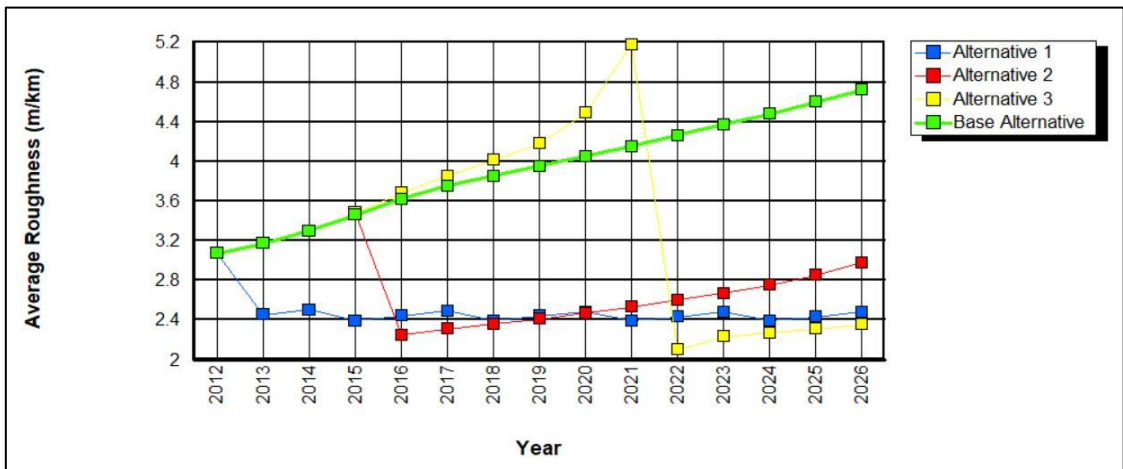


Figure 4.67 Average Roughness Progression under all alternatives for section R20

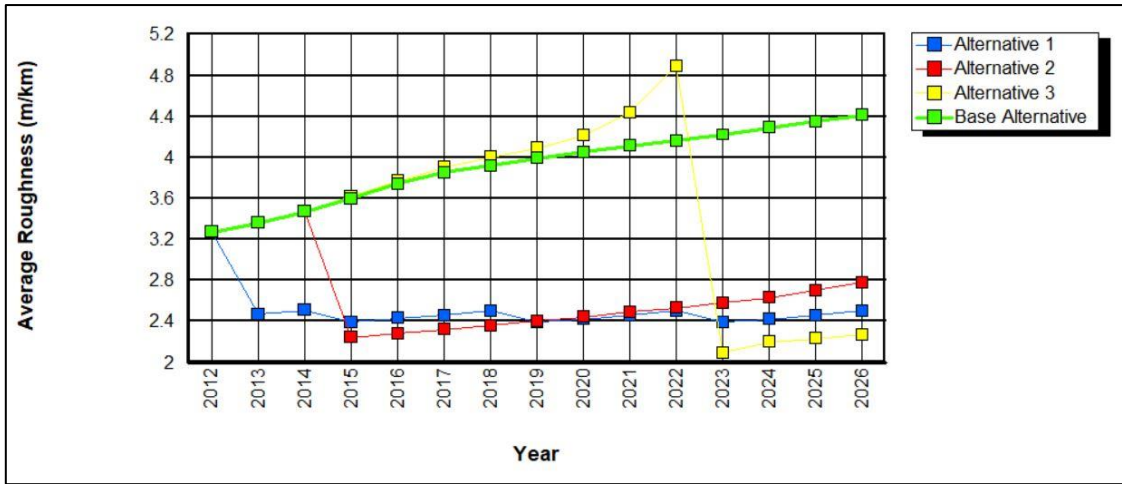


Figure 4.68 Average Roughness Progression under all alternatives for section R21

In **base alternative**, the basic patch sealing and crack seal is done. So that the pavement condition gets better. It is not a major distress maintenance technique but a basic repair strategy. So, there is not a big change in pavement condition and it is not visible openly.

In **Alternative 1**, the resealing and thin overlay is done. This has bettered the pavement condition and roughness is reduced. The interventions strike for the first time at the roughness (IRI) for R1 at 2.54 ; for R2 at the intervention 1 did not strike in because it was already above criteria of intervention; for R3 at 2.54; for R4 at 3.46; for R5 at 3.29; for R6 at 3.21; for R7 at 2.61; for R8 at 3.41; for R9 at 3.08; for R10 at 2.53; for R11 at 2.54; for R12 at 2.52; for R13 at 2.50; for R14 at 2.70; for R15 the intervention 1 did not strike in because it was already above criteria of intervention ; for R16 at 2.52; for R17, the intervention 1 did not strike in because it was already above criteria of intervention; for R18 the intervention 1 did not strike in because it was already above criteria of intervention; for R19 at 3.28; for R20 at 3.12; for R21 at 3.31;

In **Alternative 2**, the resealing and thin overlay is done. This has bettered the pavement condition and roughness is reduced. The interventions strike for the first time at the roughness (IRI) for R1 at 3.79; for R2 at 4.13; for R3 at 3.84; for R4 at 3.59; for R5 at 3.55; for R6 at 3.53; for R7 at 3.63; for R8 at 3.55; for R9 at 3.53; for R10 at 3.59; for R11 at 3.56; for R12 at 3.53; for R13, for the analysis period interventions did not

trigger; for R14 at 3.55; for R15 at 3.61; for R16 at 3.52; for R17 at 3.98; for R18 at 4.13; for R19 at 3.65; for R20 at 3.58; for R21 at 3.53;

In **Alternative 3**, the resealing and thin overlay is done. This has bettered the pavement condition and roughness is reduced. The interventions strike for the first time at the roughness (IRI) for R1 at 7.43; for R2 at 5.11; for R3 at 5.37; for R4 at 5.27; for R5 at 5.58; for R6 at 5.10; for R7 at 6.08; for R8 at 5.36; for R9 at 5.69; for R10 at 3.59; for R11 at 5.61; for R12 at 5.68; for R13, for the analysis period interventions did not trigger; for R14 at 5.44; for R15 at 5.08; for R16 at 5.62; for R17 at 5.13; for R18 at 5.09; for R19 at 5.36; for R20 at 5.64; for R21 at 5.19;

From the above graphs it can be seen that the Maintenance & Rehabilitation alternatives has come into effect at the right trigger points as defined in the work standard interventions. In the road section R13 it can be seen that reconstruction alternative has not been triggered. This is because the roughness in road section R13 has not reached the intervention limit i.e. IRI 5m/km. The value of R^2 i.e. coefficient of determination is 0.98 % and RMSE is .09 %

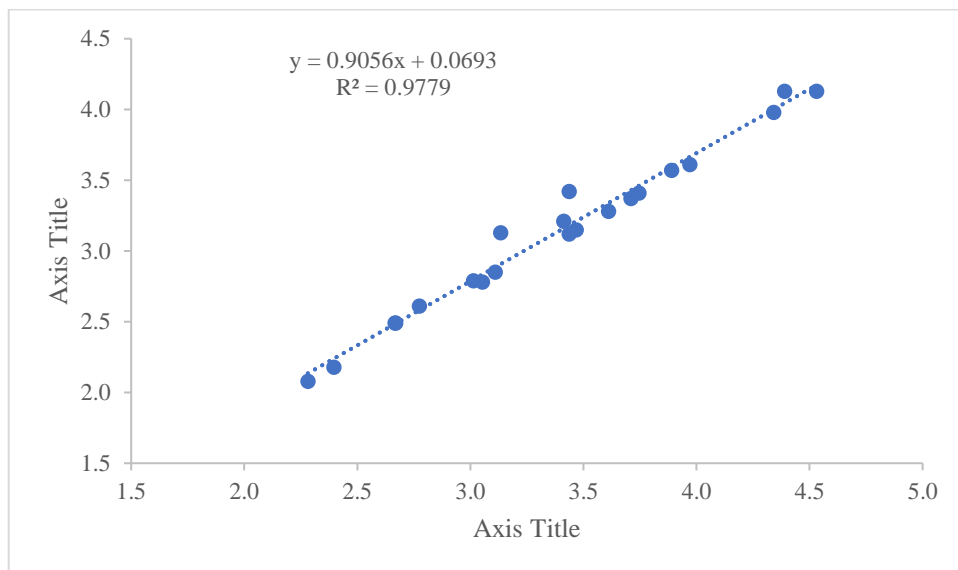


Figure 4.69 Linear Scatter Plot for Predicted Roughness vs Observed Roughness

CHAPTER 5

DISTRESS PREDICTIONS USING GENETIC PROGRAMMING MODEL AND CRRI MODEL

5.1 GENERAL

The chapter includes the processes and the technique used in the GP modelling for the pavement distresses. The data used in the generation of distress equation using GP is same that has been used in HDM-IV modelling. 'GP Kernel' programming tool has been used in the process.

5.2 INTRODUCTION TO GENETIC PROGRAMMING

Genetic Programming is an extension to the genetic algorithms that had been provided by John R. Koza (1992). GP is a technique in which programs are evolved. The process starts with a population of unfit programs, on which the operations are applied analogous to natural genetic process to the program population. The operation is selecting the fittest programs for crossover(reproduction) and mutation as per predefined measure of fitness. The swapping of random parts of the selected parents to generate a new and varying offspring that take part in new generation of programs is done in crossover operation. Dozens or hundreds of runs are required to generate very good results.

5.2.1 steps in the GP Computation

1. Creates a random initial population (Gen=0) from the available functions and terminals.
2. Check if the termination criterion is satisfied if Yes then designate the results and end the computation. If the response is No then, evaluate the fitness of every individual in population.
3. With the probability based upon fitness select programs to participate in genetic operations described below.
 - a) Reproduction; duplicate the adopted individual program to the newly generated population.

- b) Crossover; Creates new offspring programs by randomly recombining the chosen parts of a selected program.
 - c) Mutation; Creates a new offspring program for the new population by mutation of the randomly chosen parts of a selected program.
4. Once termination criterion is satisfied, the best outcome from the population is designated as result. The result can be solution to the problem if the run is successful.

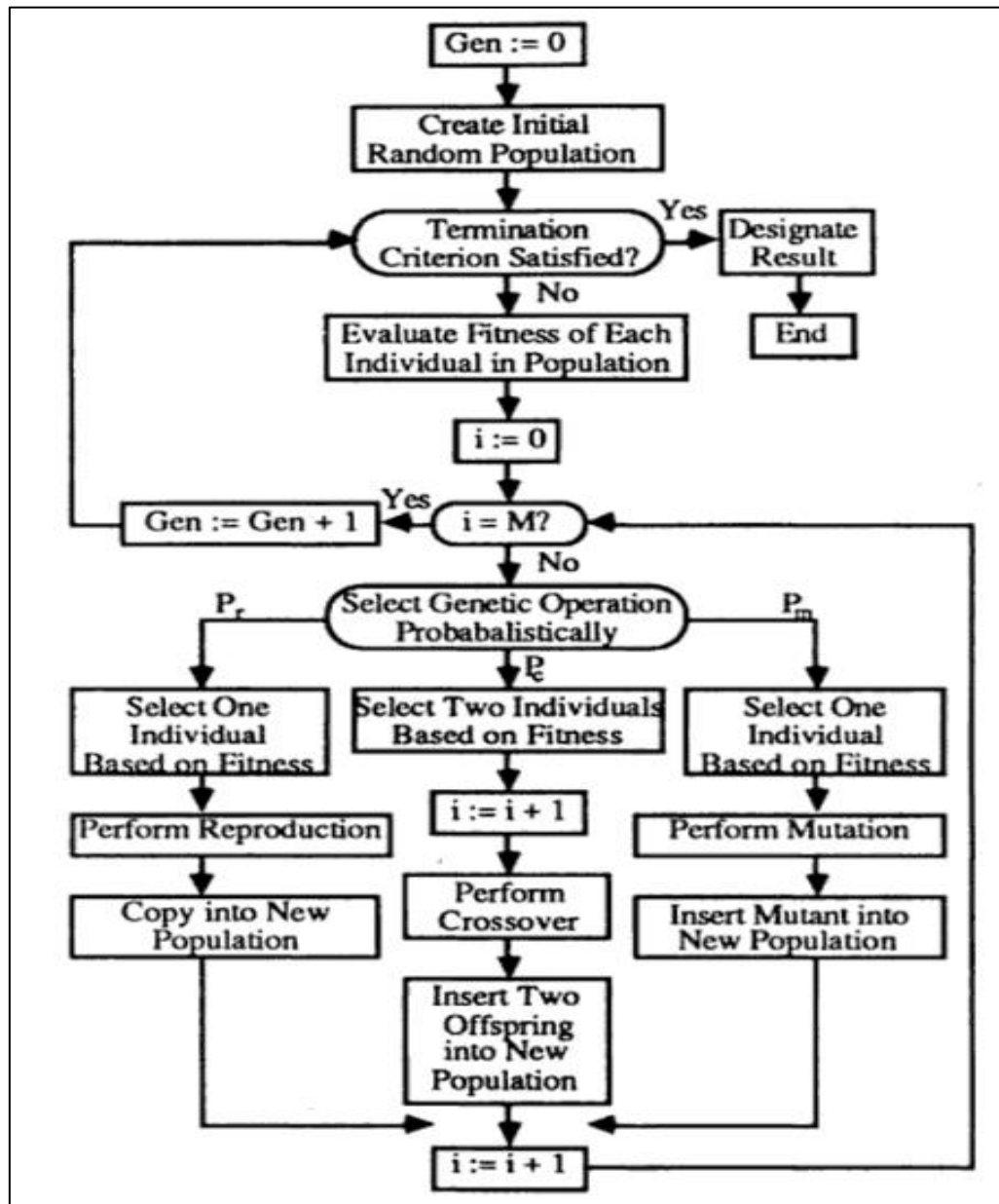


Figure 5.1 Genetic Programming Flow Chart (Koza,1992)

5.3 GP KERNEL PROGRAM

The Genetic Programming (Koza,1992) is used in the GP Kernel program to find the functions based upon the data. It a command Prompt directory-based tool with additional parameters that operates through the commands. Its working process in defined below.

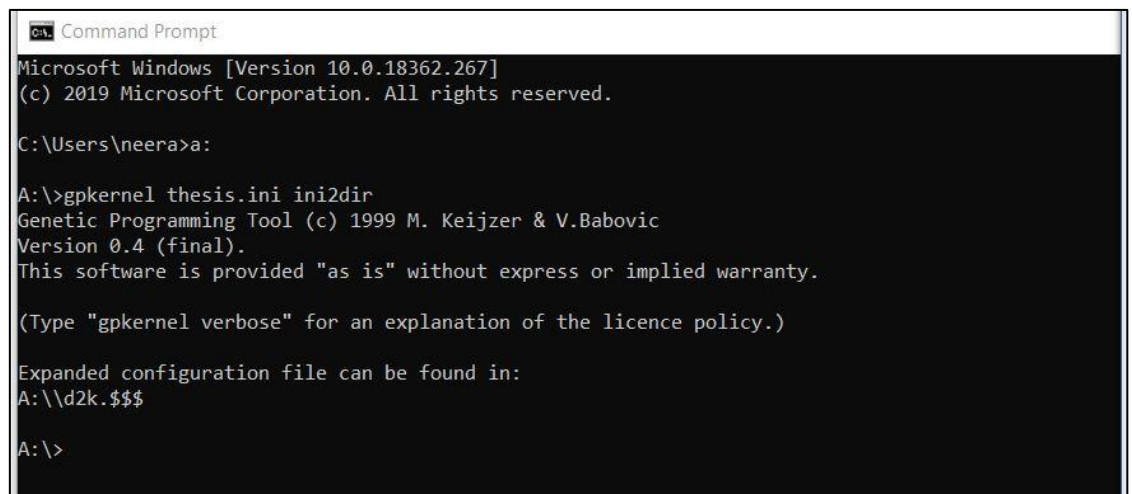
1. Data file is Created in the CSV format and saved in the GP Kernel directory.

e.g. A;\thesis.csv

2. The command to link command prompt to GP Kernel is ;

gkernel thesis.ini ini2dir

This creates a specific folder in the selected directory having all the files that are needed later.



```
Command Prompt
Microsoft Windows [Version 10.0.18362.267]
(c) 2019 Microsoft Corporation. All rights reserved.

C:\Users\neera>a:

A:\>gkernel thesis.ini ini2dir
Genetic Programming Tool (c) 1999 M. Keijzer & V. Babovic
Version 0.4 (final).
This software is provided "as is" without express or implied warranty.

(Type "gkernel verbose" for an explanation of the licence policy.)

Expanded configuration file can be found in:
A:\d2k.$$$

A:\>
```

Figure 5.2 Creation of project directory

Here, d2k.\$\$\$ is the main folder and all the data are stored inside this folder

3. The datasource file is to be changed manually in directory ' DataSource' in the 'data.ini' file to **thesis.csv**.

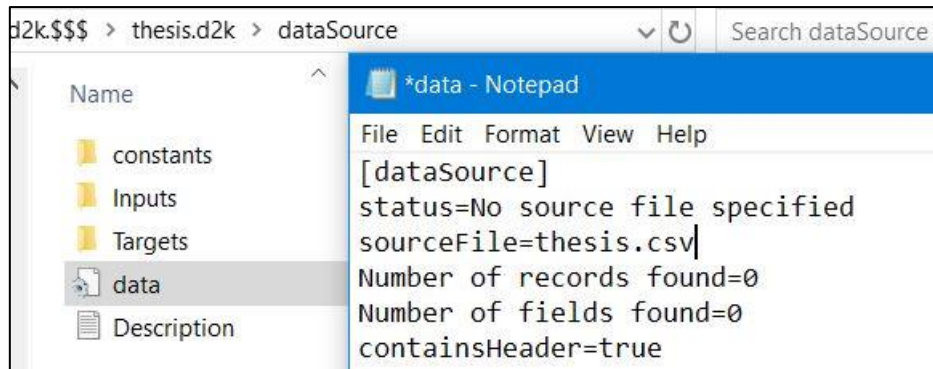


Figure 5.3 Change the data source file

4. The next step is to save the changes to the program that can be done in command prompt by the following command ;

gpkernel thesis.ini fromdir

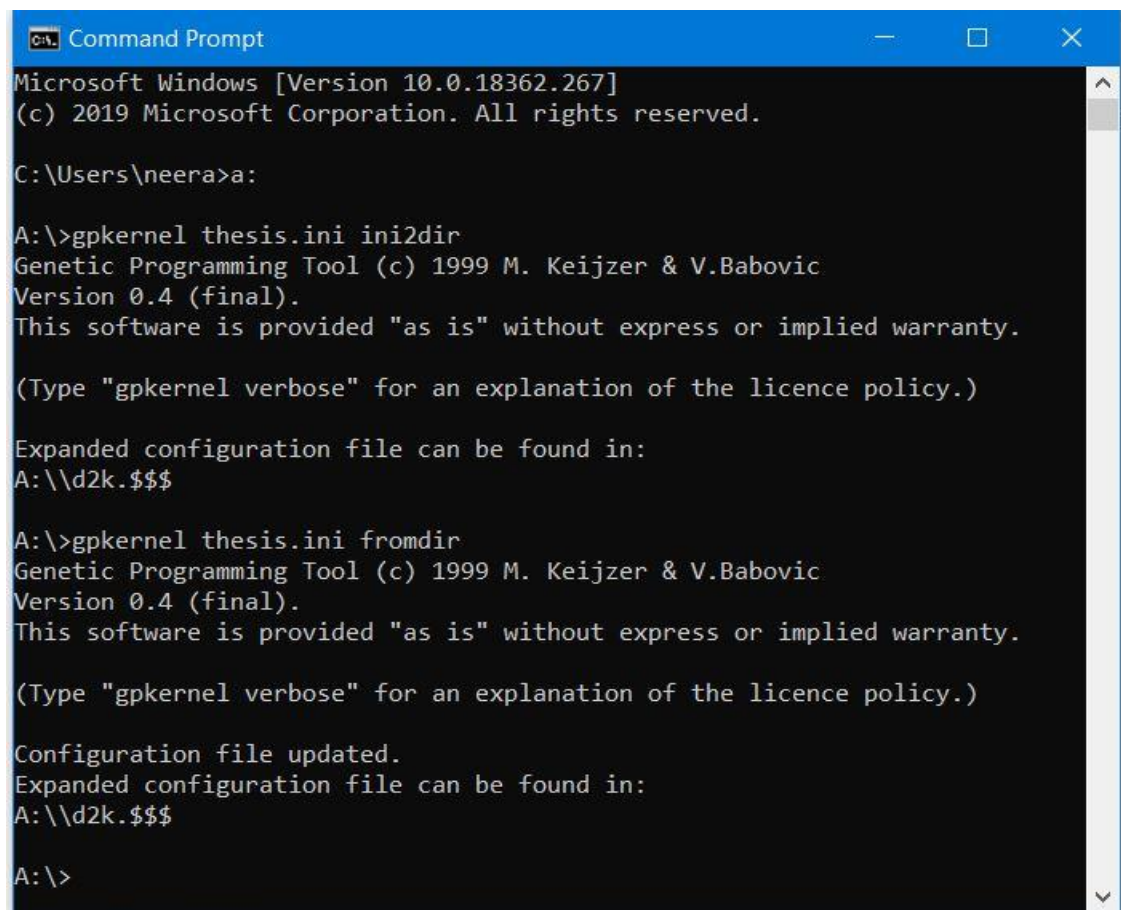


Figure 5.4 Update the changes in the GP Kernel files

5. The next step is to change all the values of different GP files as per the requirements like

dataSource

- a) Number of inputs
- b) Inputs characteristics
- c) Number of targets
- d) targets characteristics
- e) Number of constants
- f) constants characteristics

pool

- a) Number of Items
- b) Number of Experiments
- c) Time out in minutes

When the pool file values are changed then the data update command has to be run.

```
A:\>gpkernel thesis.ini fromdir
Genetic Programming Tool (c) 1999 M. Keijzer & V.Babovic
Version 0.4 (final).
This software is provided "as is" without express or implied warranty.

(Type "gpkernel verbose" for an explanation of the licence policy.)

Configuration file updated.
Pool0 is not ready yet, check parameters and status
Expanded configuration file can be found in:
A:\d2k.$$$
A:\>
```

Figure 5.5 Pool file Update from Command

6. The pool characteristics has to be changed, the same way it was changed in previous step but according to the need and type of the change.

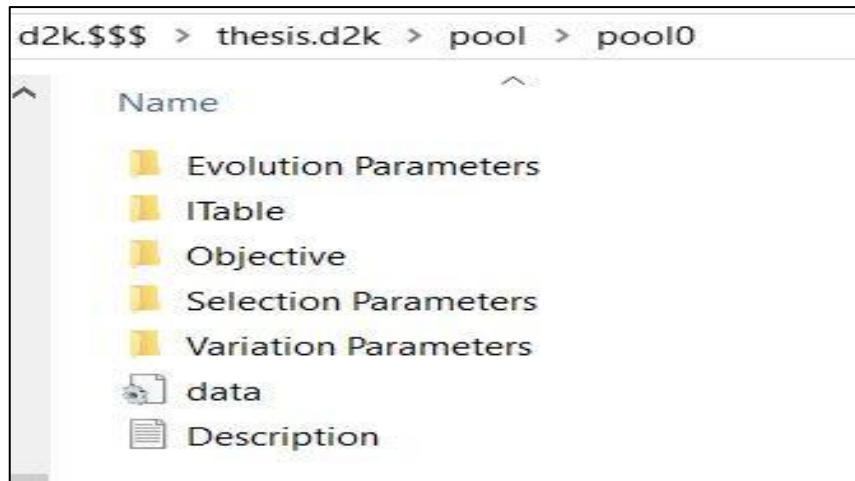


Figure 5.6 Pool characteristics

7. When all the parameters are ready in the pool and the update command has to be run again.
8. The command Prompt display that the pool is ready. If not, then there is some mistake in the initial phase that need to be rectified.
9. Last step is to go to d2k.\$\$\$ folder base directory and change the value of 'Run Experiments On Startup' to 'true' from 'false'

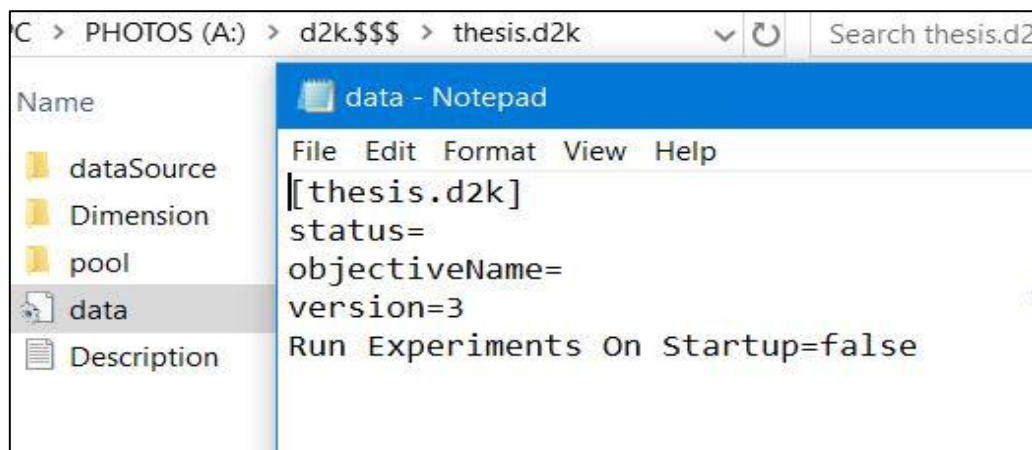


Figure 5.7 Changing Run Experiment Value to True

10. Now the file updation command has to be run in the command prompt. This will start the running of GP Kernel. The GP Kernel will run till the defined runs and the time of the experiment will directly impact the accuracy of the model

```
Command Prompt - gkernel pot.ini fromdir
Pool 0, run 0: generation 327 completed
Pool 0, run 0: generation 328 completed
Pool 0, run 0: generation 329 completed
Pool 0, run 0: generation 330 completed
Pool 0, Run estimated to end at Fri May 03 17:34:45 2019
Pool 0, Experiment estimated to end at Fri May 03 17:46:45 2019
Pool 0, run 0: generation 331 completed
Pool 0, run 0: generation 332 completed
Pool 0, run 0: generation 333 completed
Pool 0, run 0: generation 334 completed
Pool 0, run 0: generation 335 completed
Pool 0, run 0: generation 336 completed
Pool 0, run 0: generation 337 completed
Pool 0, run 0: generation 338 completed
Pool 0, run 0: generation 339 completed
Pool 0, run 0: generation 340 completed
Pool 0, run 0: generation 341 completed
Pool 0, run 0: generation 342 completed
Pool 0, run 0: generation 343 completed
Pool 0, run 0: generation 344 completed
Pool 0, run 0: generation 345 completed
Pool 0, Run estimated to end at Fri May 03 17:34:45 2019
Pool 0, Experiment estimated to end at Fri May 03 17:46:45 2019
Pool 0, run 0: generation 346 completed
```

Figure 5.8 Running Stage of the GP Kernel at Run 0

```
Command Prompt - gkernel pot.ini fromdir
Pool 0, run 7: generation 64593 completed
Pool 0, run 7: generation 64594 completed
Pool 0, run 7: generation 64595 completed
Pool 0, run 7: generation 64596 completed
Pool 0, run 7: generation 64597 completed
Pool 0, run 7: generation 64598 completed
Pool 0, run 7: generation 64599 completed
Pool 0, run 7: generation 64600 completed
Pool 0, run 7: generation 64601 completed
Pool 0, run 7: generation 64602 completed
Pool 0, run 7: generation 64603 completed
Pool 0, run 7: generation 64604 completed
Pool 0, run 7: generation 64605 completed
Pool 0, Run estimated to end at Tue Jul 30 17:38:10 2019
Pool 0, Experiment estimated to end at Tue Jul 30 17:46:40 2019
Pool 0, run 7: generation 64606 completed
Pool 0, run 7: generation 64607 completed
Pool 0, run 7: generation 64608 completed
Pool 0, run 7: generation 64609 completed
Pool 0, run 7: generation 64610 completed
Pool 0, run 7: generation 64611 completed
Pool 0, run 7: generation 64612 completed
Pool 0, run 7: generation 64613 completed
Pool 0, run 7: generation 64614 completed
Pool 0, run 7: generation 64615 completed
Pool 0, run 7: generation 64616 completed
Pool 0, run 7: generation 64617 completed
Pool 0, run 7: generation 64618 completed
Pool 0, run 7: generation 64619 completed
Pool 0, run 7: generation 64620 completed
```

Figure 5.9 Running Stage of the GP Kernel at run 7

5.4 DEVELOPMENT OF GP MODEL

GP Model has been developed using the control parameters given by Koza (1992). The Population Size (μ) has been taken as 200 and Number of Children to produce (λ) has been taken as 250. The number of generations has been set to 100000. The default values of crossover, mutation has been taken. Tournament size has been taken

as 70. The functions fabs(), exp(), sqrt(), tanh(), log(), pow(x,y), +, -, /, *,. The probability of crossover has been set to 0.8 mutation has been set to .04 .Two fitness function has been used one is R² and the other is RMSE.

5.4.1 Models generated using GP

The models generated from GP has been listed in Annexure A. There are 5 models each for Cracking, Potholes, Ravelling, Rutting and Roughness. The adopted model has been listed in table 5.1.

Table 5.1 GP Model for Distresses

DISTRESS	GP EQUATION
CRACKING	$CRA_j = (CRA_i + \sqrt{ABS(((CRA_i + (ABS(CRA_i) / (ABS((CRA_i / ((CRA_i + AGE) + CRA_i))) + (AGE + \tanh((AADT + CRA_i)))))) / ((\tanh(CRA_i) + ((ABS(AGE) + CRA_i) + \tanh(CRA_i)) + AGE))))))$
POTHOLE	$POT_j = (\text{TANH}(\text{TANH}(POT_i)) + \sqrt{((\text{TANH}(\sqrt{AADT}) * ((CRA_i * (RAV_i - 2.711)) * \text{POWER}(POT_i, CRA_i))) * CRA_i * (\text{TANH}(\text{POWER}((RAV_i - 2.607), CRA_i)) / 1.861)) / RAV_i))$
RAVELLING	$RAV_j = (\log(RAV_i) + (\log(ABS(\tanh(\log((ABS((\log(AGE) + ((\tanh(\log((RAV_i + RAV_i)))) - AADT) - \sqrt{\exp(RAV_i)})))) + RAV_i)))) + ABS(RAV_i))$
ROUGHNESS	$IRI_j = (IRI_i + \text{LOG}(\sqrt{((\sqrt{((IRI_i + \sqrt{((AADT / (RAV_i^{CRA_i})))))) / IRI_i) + \sqrt{(\sqrt{((POT_i * POT_i) + \sqrt{(\sqrt{(\sqrt{AGE}))))}) + \sqrt{((AADT / (RAV_i^{CRA_i}))))})})})$
RUTTING	$RUT_j = (RUT_i + (\tanh((BBD - \tanh((BBD * \tanh(\tanh(BBD)))))) * \sqrt{\log(\text{pow}(\log(\text{pow}((AADT / BBD), 2)), \tanh(\exp(\sqrt{\sqrt{AGE}}))))}))$

Where CRA is the Cracking, RAV is the Ravelling, RUT is the Rutting, IRI is the Roughness, POT is the Pothole, BBD is Benkelman Beam Deflection in mm i denotes the current year, j denotes next year, sqrt is Square Root, ABS is Absolute number i.e. only positive, POWER is Power, TANH is Hyperbolic Tangent

5.5 RESULTS AND DISCUSSIONS

The prediction model i.e. distress equations obtained from the GP Kernel has been shown in table 5.1 The dataset obtained in year 2011 and 2012 has been used to train the models i.e. year 2011 data has been used for the prediction of 2012 distresses. Fifteen section data has been used to train the data while other six has been used for the validation. The figures ahead have post regression fits of all models i.e. training as well as validation.

Table 5.2 Validation of the model from linear Regression

Distress Model	Training		Validation	
	R ² (%)	RMSE	R ² (%)	RMSE
Cracking	0.99	0.21	0.93	0.42
Ravelling	0.99	0.43	0.93	0.60
Pothole	0.91	0.12	0.87	0.17
Rutting	0.99	0.43	0.97	0.40
Roughness	0.90	0.14	0.99	0.07

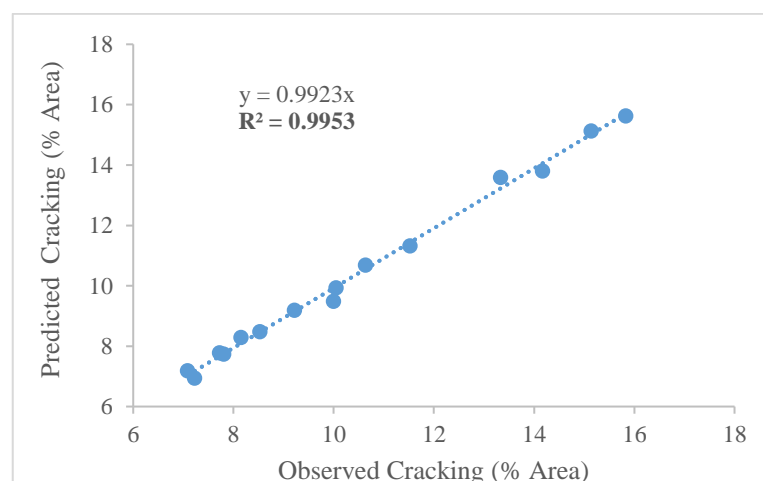


Figure 5.10 Observed vs Predicted Total Cracking (Training)

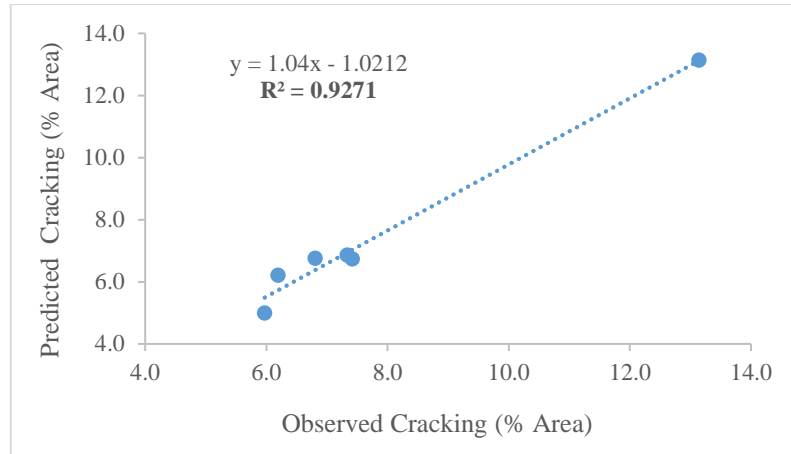


Figure 5.11 Observed vs Predicted Total Cracking (Validation)

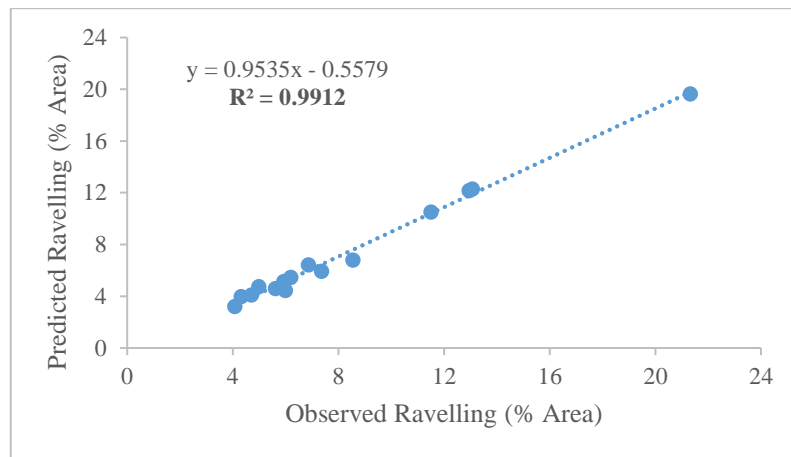


Figure 5.12 Observed vs Predicted Total Ravelling (Training)

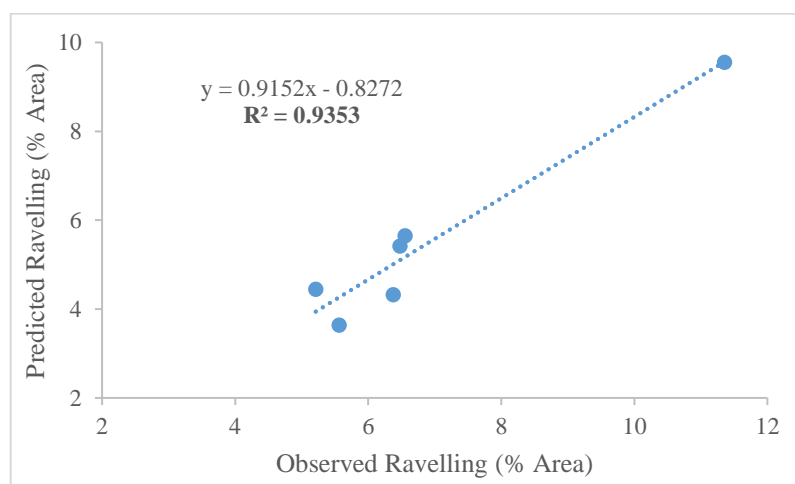


Figure 5.13 Observed vs Predicted Total Ravelling (Validation)

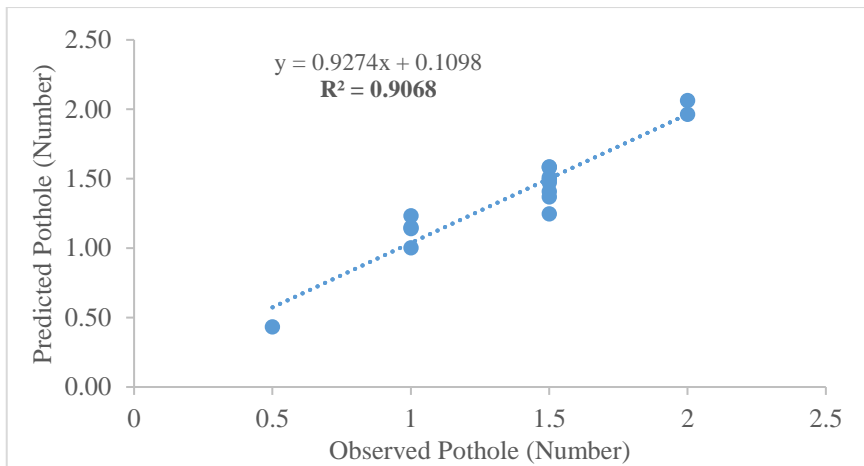


Figure 5.14 Observed vs Predicted Pothole (Training)

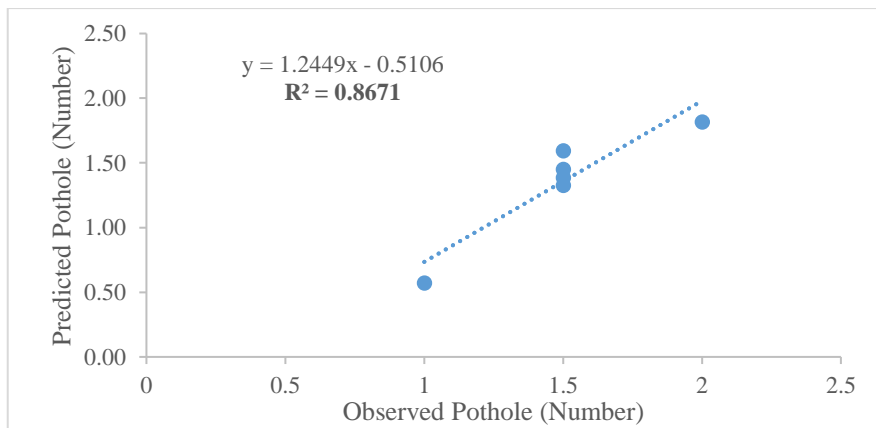


Figure 5.15 Observed vs Predicted Total Pothole (Validation)

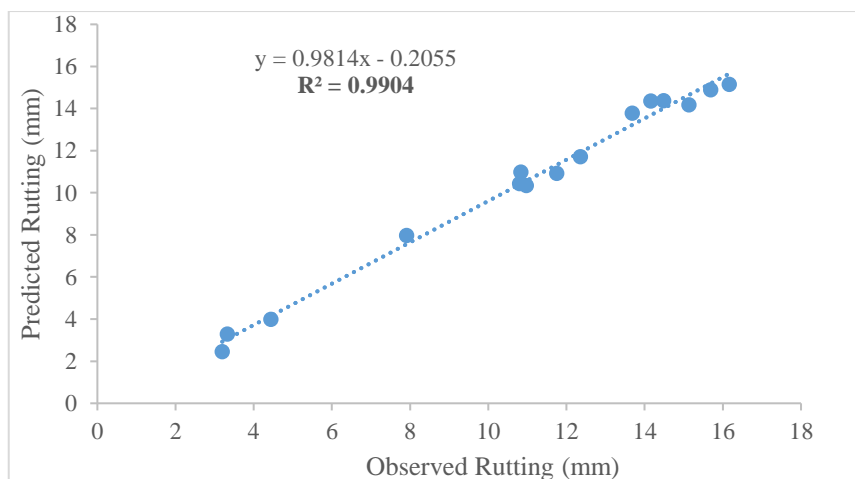


Figure 5.16 Observed vs Predicted Total Rutting (Training)

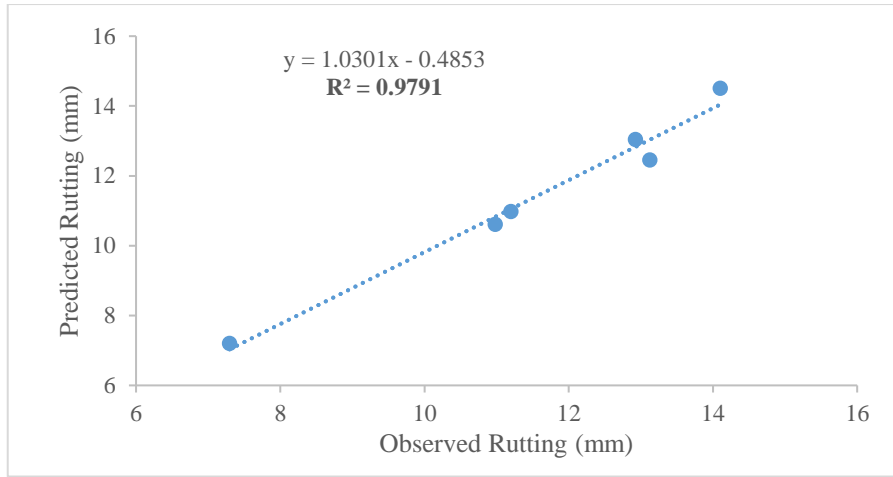


Figure 5.17 Observed vs Predicted Rutting (Validation)

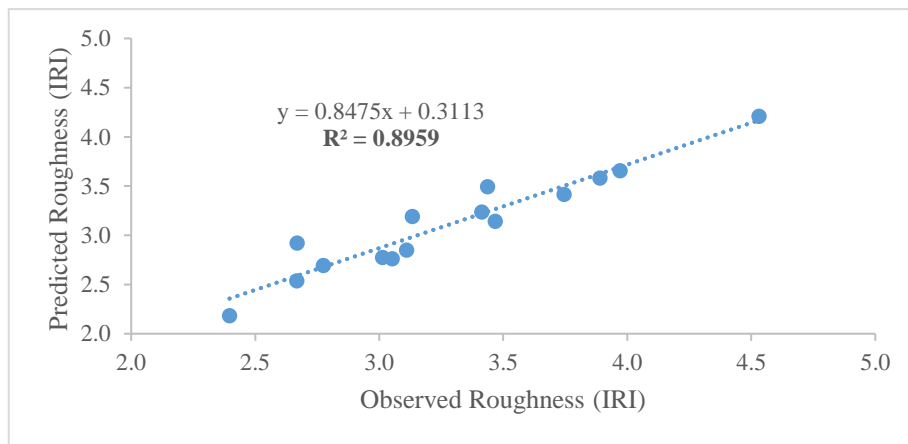


Figure 5.18 Observed vs Predicted Roughness (Training)

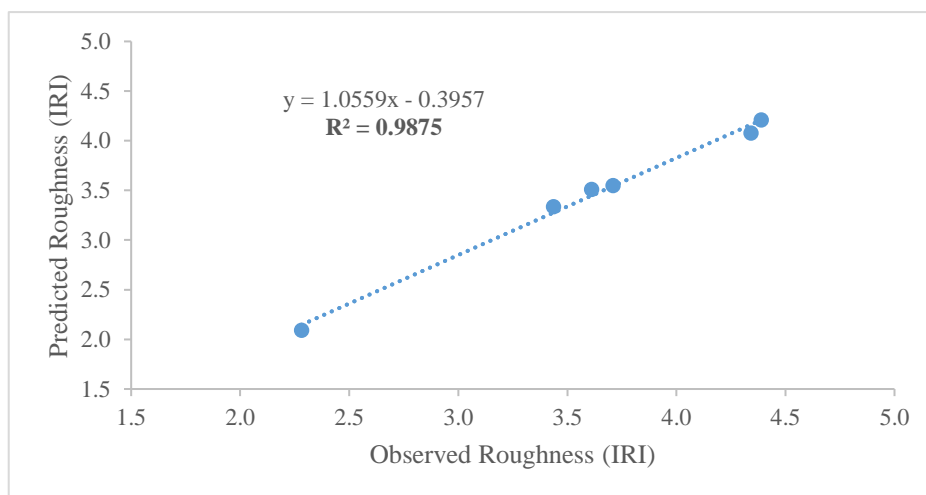


Figure 5.19 Observed vs Predicted Roughness (Validation)

From the above scatter plots, it can be seen that coefficient of determination (R^2) is very high, which is desirable. The RMSE is also good for almost all the models.

5.6 CRRI MODEL OF DISTRESSES

The CRRI model for the predictions of the pavement distresses has been developed by CRRI. The scatter plots between observed and predicted values from CRRI model has been shown below;

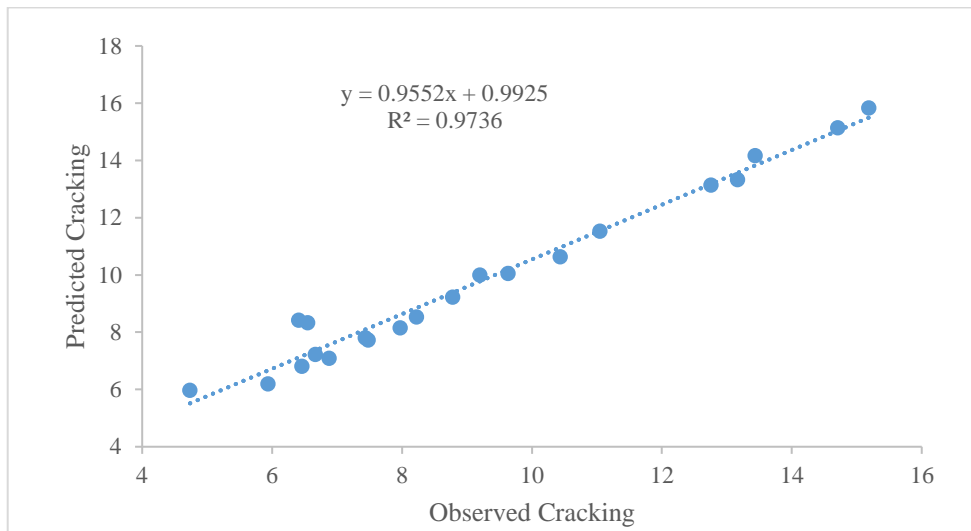


Figure 5.20 Observed vs Predicted Cracking (CRRI Model)

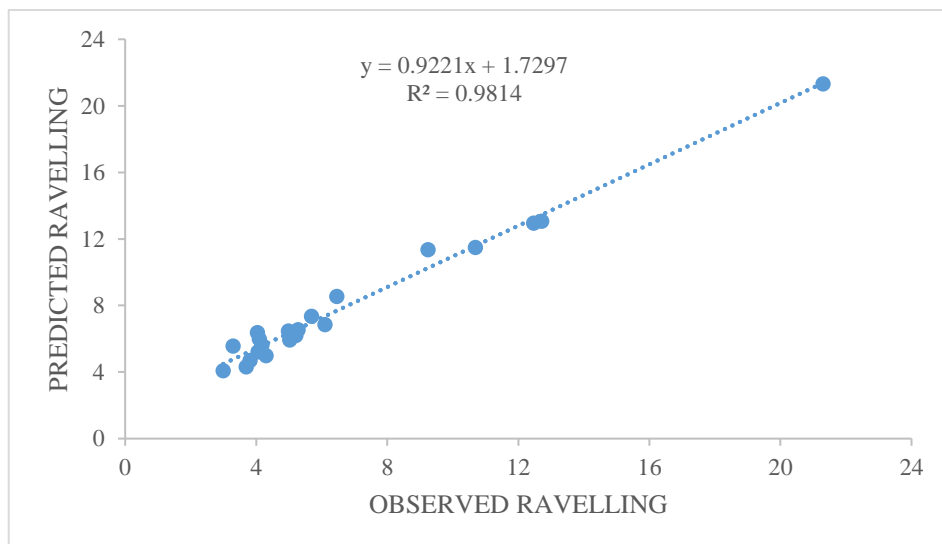


Figure 5.21 Observed vs Predicted Ravelling (CRRI Model)

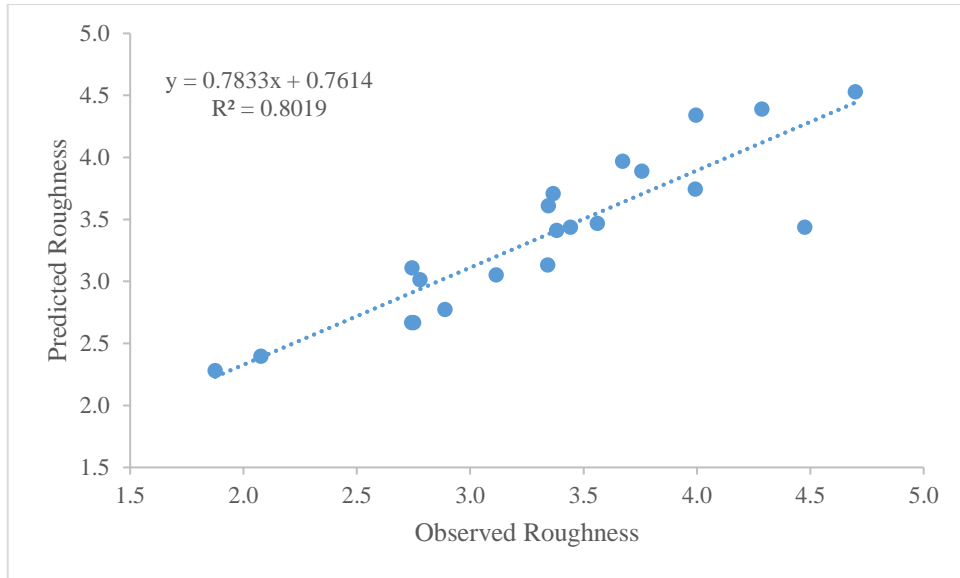


Figure 5.22 Observed vs Predicted Roughness (CRRI Model)

Table 5.3 Linear Regression Validation of CRRI model

Distress Model	Regression Equation	R²(%)	RMSE
Cracking	$y = 0.9552x + 0.9925$	0.97	0.64
Ravelling	$y = 0.7833x + 0.7614$	0.98	0.62
Roughness	$y = 0.7833x + 0.7614$	0.80	0.33

The R² values i.e. coefficient of determination is 0.97,0.98 and 0.80 for all the three models. The distresses have been predicted from the CRRI model for 3 types of distresses while model was not feasible for fourth distress i.e. pothole because the observed data had been taken in a manner that the data is very homogenous and also the very low values are there for the distress.

CHAPTER 6

RESULTS AND CONCLUSIONS

6.1 RESULTS

The obtained results from the study has been discussed and the variability of the models with respect to actual values observed has been calculated. The comparative line plot has been plotted.

Table 6.1 Variability of the Models w.r.t. Observed Values

HDM-IV MODEL	GP MODEL	CRRI MODEL
6.70	9.50	3.00
8.83	7.08	3.69
6.63	4.76	2.78
0.47	1.69	30.24
8.21	7.90	3.41
5.94	5.11	0.95
5.90	2.87	4.12
8.93	8.77	6.62
9.16	9.35	2.66
0.11	1.85	6.61
8.35	8.34	11.79
8.92	9.52	2.04
9.02	8.90	13.38
7.40	7.87	7.83
9.07	7.90	7.51
8.80	8.20	17.80
8.32	6.08	7.97
5.91	4.07	2.35
9.15	2.79	7.38
9.20	2.89	0.13
9.14	4.26	9.27

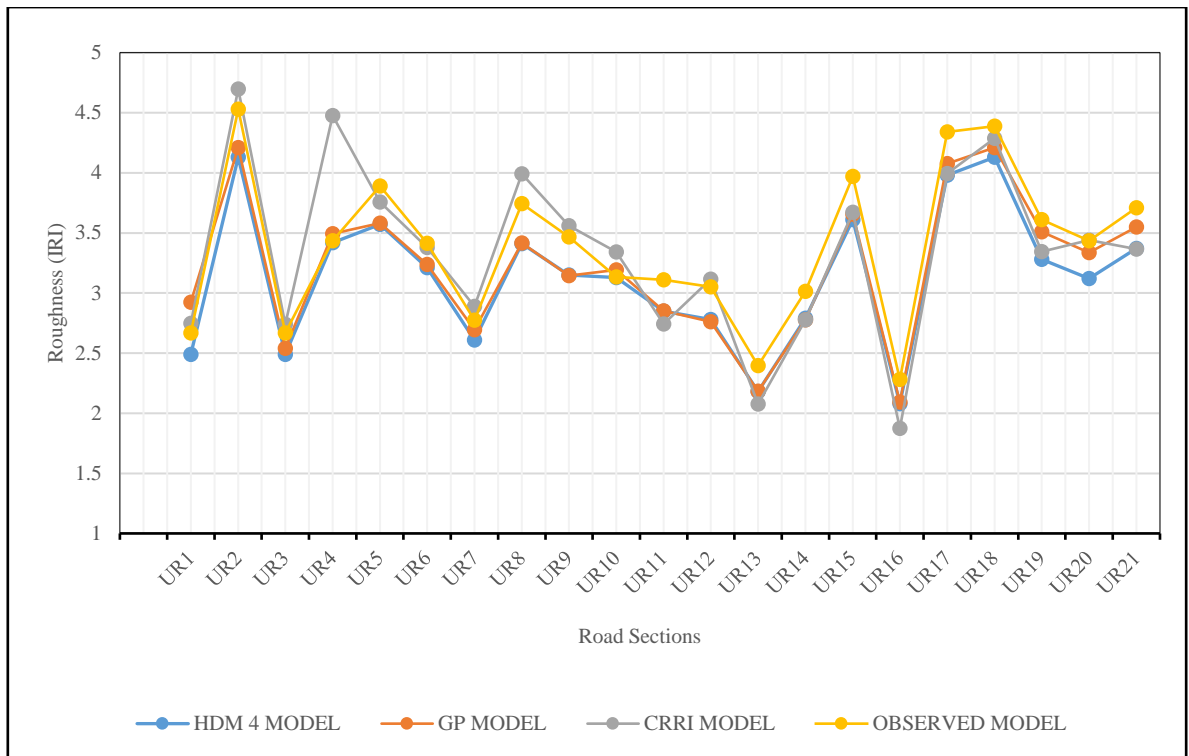


Figure 6.1 Comparative line plot between different Roughness

The models have been compared with the actual values of roughness obtained from the field. Figure 6.1, the graphical representation of the roughness obtained from various pavement deterioration models. It has been observed that GP and CRRI models both have provided values with almost same accuracy while values in CRRI model has been fluctuating in comparison to other models. In Table 6.1, variation in model distress predictions w.r.t. observed values has been calculated.

Table 6.2 Comparing Coefficients of Determination

MODEL NAME	CRRI MODEL	HDM-IV MODEL	GP MODEL
Roughness	0.80	0.98	0.90

6.2 CONCLUSIONS

The below said conclusions has been made based upon the research study;

1. The Pavement Deteriorations and their M & R strategy for road sections through various alternatives has been done for the period of fifteen years through globally recognised HDM-IV model.
2. The Remaining Service Life of the road sections has been carried out successfully. The Remaining Service life of the road sections is; R5 and R6 has 5 years of RSL; R1 and R2 has 6 years of RSL; R3, R4, R17 and R18 has 8 years of RSL; R8, R11 and R20 has 9 years of RSL; R9, R10, R19 and R21 has RSL of 10 years; R12 and R16 has 11 years of the service life; R7 has 12 years of RSL; R14 and R15 has 13 years of RSL; and R13 has 14 years of service life remaining. RSL for various sections is between 5 to 14 years.
3. Road network prioritization has been done in order to schedule the maintenance work of the road sections. More the roughness more is deterioration and hence early maintenance and rehabilitation. The sections whose RSL is lowest need Maintenance and rehabilitation at earliest.
4. Pavement Deterioration model developed by CRRRI has been used to predict the Pavement Deterioration. The model was only applicable for 3 out of the 4 distresses excluding Potholes. The R^2 of the predicted distresses was; 0.97 for Cracking, 0.98 for Ravelling and 0.80 for Roughness. Which indicates that the predicted distresses are very close to the actual observed values of the distresses.
5. Genetic Programming has been used to develop the models for the prediction of distresses and the distresses has been predicted with a very high coefficient of determination (R^2) for validation as well as training dataset. For Validation dataset R^2 has been observed as 0.93 for Cracking; 0.93 for Ravelling; 0.87 for Pothole; 0.97 for Rutting; and 0.99 for roughness.

6. The comparisons between the distresses predicted by different models on the basis of linear regression analysis has results in GP modelling coming out as the best model among all the three distress models. There is a variation of 0.11 to 9.20 in HDM-IV model, 1.69 to 9.50 in GP model, 0.13 to 30.24 in CRRI model.
7. The GP model can be very accurate but shortcoming is that the dataset was small and hence it may not be as suitable as it was for the particular network.

6.3 RECOMMENDATIONS

1. A large dataset can be used in GP so that a much more reliable and widely usable model can be developed
2. GP can be used to generate the deterioration model for the National Highways.

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