

**HEALTH MONITORING OF NATIONAL HIGHWAY NETWORK
USING HDM-4 AND GENETIC PROGRAMMING TO DEVELOP
ROAD MAINTENANCE MANAGEMENT SYSTEM**

A thesis submitted in partial fulfilment of the requirements for the award of Degree of

**MASTER OF ENGINEERING
IN
INFRASTRUCTURE ENGINEERING**

Submitted by

ABHISHEK SHARMA

801723001

Under the supervision of

Dr. Tanuj Chopra

Assistant Professor




**DEPARTMENT OF CIVIL ENGINEERING
THAPAR INSTITUTE OF ENGINEERING AND TECHNOLOGY
(A DEEMED TO BE UNIVERSITY), PATIALA, PUNJAB
JULY 2019**

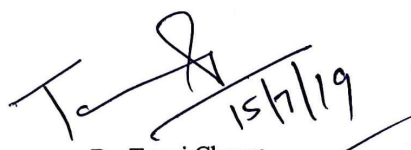
DECLARATION

I, Abhishek Sharma hereby declare that research work presented in the thesis entitled **“Health Monitoring of National Highway Network using HDM-4 and Genetic Programming to Develop Road Maintenance Management System”** is an authentic record of the work carried out during the period from 13.8.2018 to 15.7.2019 under the supervision of Dr. Tanuj Chopra (Assistant Professor) Civil Engineering Department of Thapar Institute of Engineering & Technology, Patiala as per the requirement for the award of Master of Engineering in Civil Infrastructure Engineering. The matter presented in this work has not been submitted either in part or full to any other university or institute for the award of any other degree. The author confirms that the library may lend or copy this thesis upon request for academic purposes.

Date: 15/07/2019
Place:


Abhishek Sharma
Roll no. 801723001

This is to certify that the above declaration made by the student concerned is correct according to the best of my knowledge and belief.


Dr. Tanuj Chopra
Assistant Professor
Civil Engineering Department
Thapar Institute of Engineering and Technology
Patiala, Punjab

ACKNOWLEDGEMENT

It is always a pleasure to remind the fine people in the Engineering program for their sincere guidance I received to uphold my practical as well as theoretical skills in engineering. Specifically, I would like to express my deepest gratitude to **Dr. Tanuj Chopra (Assistant Professor Civil Engineering Department)** for his invaluable expertise, co-operation, motivation and for giving me his precious time and attention. I am also thankful to our **Head of Department, Dr. Prem Pal Bansal**. A special thanks to **Dr. Palika Chopra (Assistant Professor Computer Science and Engineering Department)** for her meticulous guidance and support.

I would also like to thank my parents, brother **saurav** and friends **ashutosh, neeraj**, and **vikas** for their invaluable support and encouragement without which it would be impossible to accomplish this work.

Abhishek Sharma
M.E – CIVIL
(INFRASTRUCTURE)
801723001

TABLE OF CONTENTS

DECLARATION	i
ACKNOWLEDGEMENT	ii
LIST OF ABBREVIATIONS	vii
LIST OF TABLES	viii
LIST OF FIGURES	ix
ABSTRACT	xiv
CHAPTER – 1: INTRODUCTION	1
1.1 GENERAL	1
1.2 INDIAN ROAD NETWORK	2
1.3 INADEQUACIES OF PRESENT ROAD NETWORK SYSTEM.....	5
1.3.1 Rising Road Transport Demand.....	5
1.3.2 Poor Quality of Roads.....	5
1.3.3 Amplified Traffic Loads	6
1.3.4 Inadequate Allocation of Funds	6
1.4 RESEARCH OBJECTIVES	7
1.5 THESIS OUTLINE.....	8
CHAPTER – 2:OUTLINE OF ROAD MAINTENANCE MANAGEMENT SYSTEM AND ANATOMY OF HDM-4 MODEL	10
2.1 ROAD MAINTENANCE MANAGEMENT	10
2.2 CONSEQUENCES OF POOR MAINTENANCE TIMINGS	10
2.3 COST MARGINS.....	11
2.4 DEVELOPMENT OF RMMS	12
2.5 HDM-4 MODEL ARCHITECTURE	14
2.5.1 Data Manager Models.....	15
2.5.2 Technical Models.....	15

2.5.3 Application Modules.....	16
2.6 PAVEMENT CLASSIFICATION SYSTEM.....	17
2.6.1 Pavement Distresses.....	18
CHAPTER – 3: LITERATURE REVIEW.....	21
3.1 STUDIES CONDUCTED IN INDIA.....	21
3.2 STUDIES CONDUCTED IN ABROAD	27
CHAPTER – 4: DEVELOPMENT OF RMMS USING HDM-4 MODEL	32
4.1 GENERAL.....	32
4.2 DATA ACQUISITION.....	32
4.3 PROPOSED METHODOLOGY	33
4.4 INCORPORATION OF DATA MODELS	34
4.5 VEHICLE FLEET DATA MANAGER.....	37
4.6 PROJECT ANALYSIS.....	40
4.7 RESIDUAL SERVICE LIFE OF IDENTIFIED ROAD SECTIONS.....	42
4.8 WORK STANDARDS MODEL MANAGER.....	52
4.8.1 Maintenance Work Types	53
4.8.2 Intervention Criteria.....	54
4.8.3 Proposed Work Alternatives	54
4.9 LONG TERM PAVEMENT PERFORMANCE ANALYSIS USING HDM-4 MODEL	57
CHAPTER – 5: DEVELOPMENT OF PREDICTION MODELS USING GENETIC PROGRAMMING SYSTEM.....	68
5.1 GENERAL.....	68
5.2 SYSTEMATIC APPROACH OF GP	68
5.3 DEVELOPMENT OF DISTRESS MODELS	70
5.4 VALIDATION OF GP MODEL	72
5.5 COMPARATIVE ANALYSIS.....	75

CHAPTER – 6: ECONOMIC ANALYSIS	77
6.1 GENERAL	77
6.2 SALIENT FEATURES.....	77
6.3 METHODOLOGY	78
CHAPTER-7: CONCLUSIONS	85
7.1 MAJOR DISCOVERIES	85
7.2 SUGGESTIONS	86
REFERENCES	87
ANNEXURE	90

LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway & Transportation Officials
ANN	Artificial Neural Network
BC	Bituminous Concrete
CRRRI	Central Road Research Institute
DBM	Dense Bituminous Macadam
DBSD	Double Bituminous Surface Dressing
GA	Genetic Algorithm
GP	Genetic Programming
HDM-4	Highway Development Management Tool-4
EIRR	Economic Internal Rate of Return
LCV	Light Commercial Vehicle
MORT&H	Ministry of Road Transport and Highways
M&R	Maintenance and Rehabilitation
MT	Motorized Traffic
NH	National Highway
NHAI	National Highways Authority of India
NHDP	National Highways Development Project
NPV	Net Present Value
PMMS	Pavement Maintenance Management System
RMMS	Road Maintenance Management System
RAC	Road Agency Cost
RUC	Road User Cost
RMSE	Root Mean Square Error
RSL	Remaining Service Life
VOC	Vehicle Operating Cost

LIST OF TABLES

Table 1.1 NH Road Network across India	4
Table 1.2 Increment in Traffic Demand over the Years	5
Table 1.3 Budget Constraint Scenario of India.....	7
Table 2.1 Classification of Flexible Pavements in HDM-4.....	18
Table 2.2 Standard Flexible Pavement Distresses	18
Table 2.3 Distress Measurement Approach	20
Table 3.1 Maintenance Strategies assigned to Road Network.....	22
Table 4.1 Sectional Details	32
Table 4.2 Road Section Attributes	34
Table 4.3 Data Survey Index	35
Table 4.4 Categorization of Road Works	53
Table 4.5 Proposed Work Strategies.....	55
Table 5.1 GP Model Architecture	70
Table 5.2 Pavement Deterioration Prediction Models for National Highway Roads...	71
Table 5.4 Post-Regression Results.....	74
Table 5.5 T-Test: Paired Two Sample for Means.....	75
Table 5.6 Variability of Models in terms of Roughness Prediction	75
Table 6.1 Updated Economic Cost of Proposed Maintenance Works.....	79
Table 6.2 VOC Parameters for the Highway Traffic Composition	79
Table 6.3 Total Expenditure Cost Corresponding to Individual Maintenance Works to be Incurred by Road Agency	80
Table 6.4 Prioritization of Road Sections	84

LIST OF FIGURES

Figure 1.1 Project Map of NHDP (Source: NHAI 2003)	3
Figure 2.1 Consequences of delay in Maintenance Intervention (Shahin 1994)	11
Figure 2.2 Aftermaths of different levels of Pavement Maintenance (Robinson 1998)	12
Figure 2.3 Interrelationship between components of HDM-4 based RMMS	13
Figure 2.4 Anatomy of HDM-4 (Wightman et al 1999).....	14
Figure 2.5 Prediction of Long-term Pavement Performance (Odoki and Kerali 2000)	16
Figure 3.1 Hierarchy of OCPI.....	24
Figure 3.2 Distress Models obtained from GP for Urban Roads	26
Figure 3.3 Multi-Objective Optimization using Genetic Algorithm Tool	28
Figure 3.4 MOS Components	30
Figure 3.5 Markov Deterioration Models	31
Figure 4.1 Sectional Details	35
Figure 4.2 Pavement Historical Data and Structural Details	36
Figure 4.3 Pavement Condition Catalogue Showing various Distress Parameters	36
Figure 4.4 Calibration Factors for Surface Distress.....	37
Figure 4.5 Calibration Factors for Structural Defects.....	37
Figure 4.6 Vehicle Characteristics of Heavy Truck.....	38
Figure 4.7 Vehicular Details	38
Figure 4.8 Economic Cost Data related to Heavy Truck	39
Figure 4.9 Section-wise Traffic Count.....	39
Figure 4. 10 General Project Details	40
Figure 4.11 Sections Included for Analysis	40
Figure 4.12 Traffic Composition for Analysis.....	41

Figure 4.13 Project Analysis.....	41
Figure 4.14 Roughness Progression graph NE-1 GJ01 (KM 14-15).....	42
Figure 4.15 Roughness Progression graph NE-1 GJ02 (KM 19-20).....	43
Figure 4.16 Roughness Progression graph NE-1 GJ03 (KM 32-31).....	43
Figure 4.17 Roughness Progression graph NE-1 GJ04 (KM 15-14).....	43
Figure 4.18 Roughness Progression graph NE-14 GJ05 (KM 380.6-379.6).....	44
Figure 4.19 Roughness Progression graph NE-2 UP01.....	44
Figure 4.20 Roughness Progression graph NE-2 UP02.....	44
Figure 4.21 Roughness Progression graph NH-37AS (KM 177.30-178.30).....	45
Figure 4.22 Roughness Progression graph NH-4 KA01 (KM 46-45).....	45
Figure 4.23 Roughness Progression graph NH-4 KA02 (KM 481-482).....	45
Figure 4.24 Roughness Progression graph NH-4 KA03 (KM 82-83).....	46
Figure 4.25 Roughness Progression graph NH-5 AP01 (KM 691.25-690.75).....	46
Figure 4.27 Roughness Progression graph NH-5 AP03 (KM 7.5-7).....	47
Figure 4.28 Roughness Progression graph NH-5 AP04 (KM 9.8-9.3).....	47
Figure 4.29 Roughness Progression graph NH-4 MH01 (KM 539-538).....	47
Figure 4.30 Roughness Progression graph NH-7 MH02 (KM 84.2-84.7).....	48
Figure 4.31 Roughness Progression graph NH-7 MH03 (KM 95.5-96).....	48
Figure 4.32 Roughness Progression graph NH-73 (KM 0-11).....	48
Figure 4.33 Roughness Progression graph NH-73 02 (KM 11-25).....	49
Figure 4.34 Roughness Progression graph NH-73 03 (KM 25-35).....	49
Figure 4.35 Roughness Progression graph NH-73 04 (KM 35-47).....	49
Figure 4.36 Roughness Progression graph NH-74 (KM 0-13).....	50
Figure 4.37 Roughness Progression graph NH-74 02 (KM 13-30).....	50
Figure 4.38 Roughness Progression graph NH-72 01 (KM 105-118).....	50
Figure 4.39 Roughness Progression graph NH-72 02 (KM 118-132).....	51

Figure 4.40 Roughness Progression graph NH-72 03 (KM 132-148).....	51
Figure 4.41 Roughness Progression graph NH-72 04 (KM 162-180).....	51
Figure 4.42 Roughness Progression graph NH-72 05 (KM 180-197).....	52
Figure 4.43 Alternatives Defined for Project Analysis.....	55
Figure 4.44 Base Alternative (Routine Maintenance)	56
Figure 4. 45 Intervention Limits for Alternative 2	56
Figure 4. 46 Intervention Limits for Alternative 3	57
Figure 4.47 Average Roughness Trend of NE-1 GJ01 (KM 14-15) for Maintenance Standards.....	58
Figure 4.48 Average Roughness Trend of NE-1 GJ02 (KM 19-20) for Maintenance Standards.....	58
Figure 4.49 Average Roughness Trend of NE-1 GJ03 (KM 32-31) for Maintenance Standard	58
Figure 4.50 Average Roughness Trend of NE-1 GJ04 (KM 15-14) for Maintenance Standards.....	59
Figure 4.51 Average Roughness Trend of NH-14GJ (KM 380.6-379.6) for Maintenance Standards.....	59
Figure 4.52 Average Roughness Trend of NH-2UP 01 for Maintenance Standards....	59
Figure 4.53 Average Roughness Trend of NH-2UP 02 for Maintenance Standards....	60
Figure 4.54 Average Roughness Trend of NH-37AS (Km 177.30-178.30) for Maintenance Standards	60
Figure 4.55 Average Roughness Trend of NH-4 KA01 (KM 46-45) for Maintenance Standards.....	60
Figure 4.56 Average Roughness Trend of NH-4 KA 02 (KM 481-482) for Maintenance Standards.....	61
Figure 4.57 Average Roughness Trend of NH-4 KA03 (KM 82-83) for Maintenance Standards.....	61

Figure 4.58 Average Roughness Trend of NH-5 AP01 (Km 691.25-690.75) for Maintenance Standards	61
Figure 4. 59 Average Roughness Trend of NH-5 AP02 (KM 698.6-698.1) for Maintenance Standards	62
Figure 4.60 Average Roughness Trend of NH-5 AP03 (KM 7.5-7) for Maintenance Standards.....	62
Figure 4.61 Average Roughness Trend of NH-5 AP04 (KM 9.8-9.3) for Maintenance Standards.....	62
Figure 4.62 Average Roughness Trend of NH-4 MH01 (KM 539-538) for Maintenance Standards.....	63
Figure 4.63 Average Roughness Trend of NH-7 MH02 (KM 84.2-84.7) for Maintenance Standards.....	63
Figure 4.64 Average Roughness Trend of NH-7 MH03 (KM 95.6-96) for Maintenance Standards.....	63
Figure 4.65 Average Roughness Trend of NH-73 01 (KM 0-11) for Maintenance Standards.....	64
Figure 4.66 Average Roughness Trend of NH-73 02 (KM 11-25) for Maintenance Standards.....	64
Figure 4.67 Average Roughness Trend of NH-73 03 (KM 25-35) for Maintenance Standards.....	64
Figure 4.68 Average Roughness Trend of NH-73 04 (KM 35-47) for Maintenance Standards.....	65
Figure 4.69 Average Roughness Trend of NH-74 01 (KM 0-13) for Maintenance Standards.....	65
Figure 4.70 Average Roughness Trend of NH-74 02 (KM 13-30) for Maintenance Standards.....	65
Figure 4.71 Average Roughness Trend of NH-72 01 (KM 105-118) for Maintenance Standards.....	66

Figure 4.72 Average Roughness Trend of NH-72 02 (KM 118-132) for Maintenance Standards.....	66
Figure 4.73 Average Roughness Trend of NH-72 03 (KM 132-148) for Maintenance Standards.....	66
Figure 4.74 Average Roughness Trend of NH-72 04 (KM 162-180) for Maintenance Standards.....	67
Figure 4.75 Average Roughness Trend of NH-72 05 (KM 180-197) for Maintenance Standards.....	67
Table 5.3 Validation Dataset.....	72
Figure 5.2 Validation of Cracking Model.....	73
Figure 5.3 Validation of Ravelling Model.....	73
Figure 5.4 Validation of Rutting Model	73
Figure 5.5 Validation of Roughness Model.....	74
Figure 5.6 Comparison of HDM and GP model in terms of Roughness (IRI) Prediction Capabilities	76

ABSTRACT

With the increasing traffic loads on National highways of India, pavements are deteriorating at a faster rate leading to premature failure. In addition to this lack of scientific road management system leads to lower levels of serviceability and unreliable road network in the long term. Therefore, in order to maintain the highway network in good condition the road administration should focus on long lasting and economical road maintenance solutions.

The research study focuses on the development of road management system for high volume roads using calibrated HDM-4 model. Long term pavement performance under various maintenance strategies has been measured in terms of roughness progression using HDM. The most appropriate maintenance strategy has been identified using the life-cycle cost analysis based on NPV/COST ratio parameter. GP system has been configured to develop four distress prediction models i.e., roughness, ravelling, cracking and rutting. Adequacy of GP models has been measured using simple linear regression analysis. Statistical significance of roughness model has been evaluated using student's T-Test. Variability in the output results of the two deterministic models i.e., HDM and GP has been computed by comparing the difference between predicted and observed roughness behaviour.

Prediction models play a crucial role in development of RMMS for systematic technical as well as economic appraisal of road projects. Future modelling of pavement behaviour and cost streams related to various maintenance activities will assist the highway planners and road agencies in timely monitoring and conditioning of roads by adopting suitable management framework.

CHAPTER – 1

INTRODUCTION

1.1 GENERAL

India is a diverse country with second largest road network out of which national highways holds a share of 1.80 % (MORT&H). Road transportation plays a crucial role in overall economic growth of country owing to its flexibility, accessibility, reliability and door-to-door service. Infrastructure development primarily consists of road transportation facilities such as expansion and upgradation of road networks, efficient connectivity to towns and cities ensuring seamless travel. Road projects require large capital investment and therefore timely allocation and utilization of funds is necessary for conditioning of roads and providing safe passage at appropriate speed and optimized road user cost. Due to lack of decentralisation of funds in India, the funds allocated for maintenance does not exceed 60% of the normal requirements of roads (MORT&H 2001b). This gap between the requirements and allocation has been accumulating over the years and is a grave concern for the long term pavement performance. With the exponential growth in automobile industry, the traffic volume plying on roads has been increasing day by day inducing higher strain within the pavement structure. Also with the introduction of heavier and longer commercial vehicles the pavement deterioration occurs at a much higher rate leading to structural failure of pavement before the estimated design life. To enhance the pavement performance, conditioning of road pavements needs to be done at regular intervals. It has been observed that delay in maintenance and rehabilitation of roads leads to faster pavement deterioration, increase in vehicle operating costs and accident costs thereby reducing the reliability of road network. Further if the pavement maintenance work is delayed even after noticeable deterioration, there comes a break point after which only reconstruction or extensive rehabilitation can be done costing many times more than routine maintenance works. Late or inadequate maintenance and rehabilitation works leads to increase in road agency cost and road user cost and consequently reduces safety and reliability of road network. Timely implemented maintenance and rehabilitation strategies bags a remarkable serviceability level for the road agencies. The main goal of highway engineers should be to accomplish a healthy pavement condition index in terms of both functional as well as structural condition keeping in mind other aspects such as

economic, safety and environment. Road maintenance and investment projects both require strategic planning and enormous funding. Therefore, a decision support system needs to be adopted by transportation agencies for selection of optimum maintenance works within the budget constraint.

1.2 INDIAN ROAD NETWORK

India is second to United States in road network with a total road length of 59,03,293 kilometres as of 31st January, 2019. It is very vital for the economic growth of country as transportation sector alone contributes 4.7 % towards gross domestic product. Under the government launched scheme National Highway Development Programme (NHDP), a lot of road projects especially upgradation to two-lane with paved shoulders and rehabilitation in road widening projects have been flagged off by National Highways Authority of India (NHAI) as shown in Figure 1.1. The main goal of NHDP scheme is development of national highways to establish seamless travel for both the passenger and freight traffic across the entire nation. Widening and strengthening of existing NH will minimize congestion and disruption to traffic movement and thereby achieving user safety and high ridership quality.

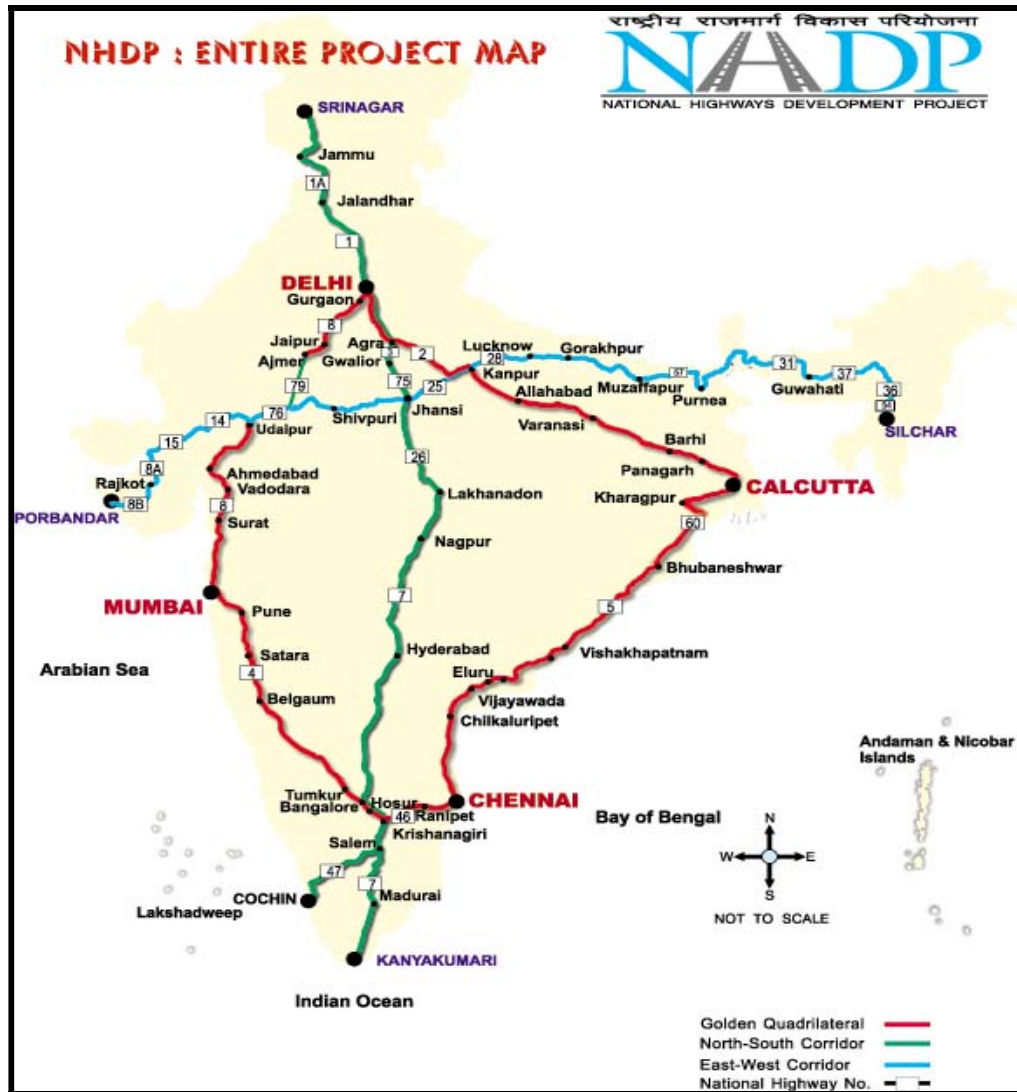


Figure 1.1 Project Map of NHDP (Source: NHA 2003)

NHAI is the sole authority at the apex who is responsible for the planning and implementation of highway projects to ensure efficient connectivity between towns, cities and major ports. The total length covered by National Highways as of November 2018 is 1,31,326 km and is increasing at a higher pace. Table 1.1 depicts road length of national highways in various parts of India.

Table 1.1 NH Road Network across India

Sr. No.	State/UT	Total Length (in km)
1	Andhra Pradesh	6,529
2	Arunachal Pradesh	2,537
3	Assam	3,909
4	Bihar	5,031
5	Chandigarh	15
6	Chhattisgarh	3,606
7	Delhi	111
8	Goa	293
9	Gujarat	6,635
10	Haryana	3,098
11	Himachal Pradesh	2,607
12	Jammu & Kashmir	2,423
13	Jharkhand	3,367
14	Karnataka	7,335
15	Kerala	1,782
16	Madhya Pradesh	8,772
17	Maharashtra	17,757
18	Manipur	1,750
19	Meghalaya	1,156
20	Mizoram	1,423
21	Nagaland	1,548
22	Odisha	5,762
23	Puducherry	27
24	Punjab	3,270
25	Rajasthan	9,999
26	Sikkim	463
27	Tamil Nadu	6,742
28	Telangana	3,795
29	Tripura	854
30	Uttar Pradesh	11,737
31	Uttarakhand	2,949
32	West Bengal	3,664
33	A & N Islands	331
34	Dadra & Nagar Haveli	31
35	Daman & Diu	22
		1,31,326

Source: NHAI (2019)

1.3 INADEQUACIES OF PRESENT ROAD NETWORK SYSTEM

In the past decade or so there has been a boom in the demand for road transportation in India but unlikely the quality standards have not been up to the mark. The gap between the quality and capacity standards have hampered the growth of road infrastructure of India. Major inadequacies have been highlighted below:

1.3.1 Rising Road Transport Demand

With the innovation of advanced technologies in the automobile industry, remarkable growth of road traffic has been observed. Both the passenger vehicles and commercial vehicles have seen an incredible growth over the last 50 years. Unprecedented growth in share of road transport in passenger and freight movement has escalated by 20% to 85% and 20% to 70% respectively. Also there has been a noticeable shift in passenger and freight transportation by roads in comparison to rails. Table 1.2 depicts increment in number of vehicles over last 50 years.

Table 1. 2 Increment in Traffic Demand over the Years

Year	Total No. of Vehicles (in thousands)	Commercial Vehicles (in thousands)
1951	306	116
1961	665	225
1971	1865	437
1981	5391	716
1991	21374	1687
1995	30295	2217
1997	37231	2748
2000	48393	3240
2005	70000*	4500*

* Estimated figures

Source: MORT&H (2001c) and NHAI (2003)

1.3.2 Poor Quality of Roads

The structural condition of roads is poor primarily due to lack of proper and timely maintenance measures and therefore large part of road network remains unpaved or massively deteriorated. Road pavements are subjected to varying traffic loads and temperature conditions which leads to aging and generates various kind of distresses viz. cracking, rutting, ravelling and potholing within the pavement structure. Structural adequacy of NH and SH to carry permissible standard axle load (10.2 tonnes) for the

projected design life is very less and only 15% of them can cater the aforementioned traffic loads (MORT&H 2001c).

1.3.3 Amplified Traffic Loads

The annual traffic growth rate on Indian roads as predicted by MORT&H is quantified as 10%. This exponential growth in road transport has put a capacity constraint on existing road network and demands expansion of network system in terms of lane capacity and structural adequacy to cater the growing needs. Also the freight transport which includes commercial vehicles are plying on roads at a higher axle load of about 18-22 tonnes exceeding the prescribed legal axle load limit of 10.2 tonnes (MORT&H). Thus to overcome this overloading effect the existing road pavement structure needs to be strengthened and upgraded to enhance the long term pavement performance. Well planned and timely implemented maintenance and improvement measures are the key solutions to compensate for this escalating pavement deterioration and preservation of road serviceability levels.

1.3.4 Inadequate Allocation of Funds

Road agencies in India have to face a major issue regarding deficit funds allocated to them by the concerned authorities. The funds allocated for maintenance only cover a total of 60% of the actual requirements of roads. In addition to this the tremendous rise in traffic in terms of volume and axle loads poses a severe risk to the pavement service quality. Therefore, proper allocation and timely utilisation of funds for road maintenance and improvement measures will help preserve acceptable pavement conditions for the road users. Table 1.3 depicts the gap between fund allocations and fund requirements for road management strategies for National Highways.

Table 1.3 Budget Constraint Scenario of India

Year	Requirements (Rs. Crores)	Allocations (Rs. Crores)	Shortfall (Rs. Crores)	% Shortfall
1981-82	55.55	47.00	8.55	15.39
1982-83	60.00	51.00	9.00	15.00
1983-84	71.90	61.00	10.00	15.16
1984-85	108.30	75.00	33.30	30.75
1985-86	116.82	90.00	26.82	22.96
1986-87	176.78	94.25	82.53	46.69
1987-88	177.24	99.03	78.21	44.13
1988-89	198.00	142.36	55.64	28.10
1989-90	194.50	143.55	50.95	26.20
1990-91	257.91	153.12	104.79	40.63
1991-92	291.29	166.76	124.53	42.75
1992-93	330.00	168.67	161.33	48.89
1993-94	415.00	214.50	200.50	48.31
1994-95	475.00	246.90	228.10	48.00
1995-96	535.00	288.43	246.57	46.09
1996-97	570.00	372.00	198.00	34.74
1997-98	600.00	497.50	102.50	17.08
1998-99	1050.00	549.80	500.20	47.63
1999-2000	1250.00	703.00	547.00	43.76

Source: MORT&H (2001b)

1.4 RESEARCH OBJECTIVES

The primary objective of this study is to develop a scientific framework which will assist the road agencies involved in highway maintenance works and provide the monetary bodies responsible for sanctioning of budget with cost effective solutions related to long term pavement performance. HDM-4 is a pavement management tool which predicts the best possible maintenance alternative based on economic analysis and offers budget prioritization under constrained budget scenario. RMMS has been developed using HDM-4 tool for strategic planning and economic analysis of maintenance strategies to be adopted for 29 road sections of National Highway network. The study is oriented to various geographical locations, climatic conditions, pavement carriageway sections and traffic composition. The pavement surface types of all the above mentioned road sections are flexible in nature having asphalt mix on granular base. The scope of study incorporates the following:

- Extensive Literature review on past research developments related to scientific approach behind development of road management system in India.
- Collection of road network data for the selected national highways network including road inventory data, traffic volume data, pavement distress survey data required for generating HDM-4 model from various publications.
- Prediction of residual service life of road pavements on the basis of life-cycle pavement performance to adopt suitable maintenance and/or improvement works.
- Development of scientific road management system for National Highways for the selection of best possible M&R strategy using the economic analysis application in HDM.
- Genetic Programming has been thoroughly analysed and tailored to develop pavement distress prediction models. Validation of GP prediction models using statistical techniques to check the efficacy of the distress models. Comparison of HDM-4 and GP models in terms of similarity and adequacy.

1.5 THESIS OUTLINE

- Chapter 1 includes introduction to present scenario of Indian road network and paucity of road management system. Various deficiencies of road network such as insufficient availability of funds and early deterioration of Indian roads due to escalating traffic demand and lack of scientific road management system have been discussed. Research objectives of the study have been described.
- Chapter 2 highlights the fundamental need of establishing a systematic road appraisal system. It emphasizes on the role of RMMS in development of a reliable and efficient road network system and achieve target serviceability levels. The analytical framework of HDM-4 software program consisting of various in-built data models and application tools have been pointed out in this chapter. Concept of life cycle analysis has been implemented in this study to develop RMMS. Further the pavement distresses predominant in flexible pavements have been briefly described.
- Chapter 3 includes the extensive literature review of the implementation of road management system in various geographical locations across the globe over the past few decades. Numerous software programs and analytical techniques to develop RMMS have been discussed in this chapter. Due to the wide range of

applicability and adequacy, study recommends HDM-4 as road appraisal system to road agencies.

- Chapter 4 explains the hierarchical process involved in establishing a road management system for National Highways road network. Firstly, the study area has been identified which includes 29 road sections of NH road class in various geographical locations in India. Input data pertaining to identified road network such as road pavement attributes and cost data have been gathered from various publications. Using the project level analysis application tool in HDM the long term pavement performance has been determined. Road maintenance strategies have been adopted to target optimum serviceability levels applicable for NH road network. Roughness has been kept as the governing performance parameter and based on this the residual life of road sections have been determined.
- Chapter 5 illustrates the use of Genetic Programming technique for development of distress models predictive in nature. The anatomy of GP consisting of various control parameters and scientific approach has been explained in this chapter. Validation of distress prediction models to measure the efficacy of these models have been done using statistical evaluation techniques.
- Chapter 6 includes economic analysis to determine optimal pavement management solution for the road network. HDM provides the highway engineers with cost effective solutions which can be customized according to the budget scenario and serviceability standards. In this chapter optimum maintenance strategy has been identified on the basis of maximum NPV/ COST ratio and maintenance scheme has been established for a period of 20 years.
- Chapter 7 highlights the major discoveries obtained from the research study and offers future work proposals.

CHAPTER - 2

OUTLINE OF ROAD MAINTENANCE MANAGEMENT SYSTEM AND ANATOMY OF HDM-4 MODEL

2.1 ROAD MAINTENANCE MANAGEMENT

World bank carried extensive research on pavement maintenance and management and concluded that road maintenance works generates higher economic rate of return as high as 50% when compared to investment on reconstruction. Thus it becomes essential to develop optimum maintenance and rehabilitation (M&R) strategies and an economic analysis framework before expansion of road network to check the technical as well as economic viability of project in hand. Highway development & management (HDM) software program was invented by the World Bank back in 1951 which serves as a decision support system for the road agencies dedicated towards road maintenance and road investment projects. It is a road appraisal system which determines the feasibility of projects in terms of technical as well as economic aspects and predicts economic indicators like Net Present Value (NPV) and Internal Rate of Return (IRR). Road agencies and concerned state bodies in India still rely on the conventional approach of handling and managing projects and gives least priority to future road maintenance strategies. Inadequacy of road maintenance works have severely deteriorated the pavement service quality and shattered road user economy as poorly maintained roads lead to accidents, traffic congestion and higher Vehicle operating costs (VOC) and Travel time cost (TTC). Basic fundamental principal is that for longevity of good condition roads, timely monitoring and conditioning of roads through establishing suitable maintenance work standards is a necessity.

2.2 CONSEQUENCES OF POOR MAINTENANCE TIMINGS

As stated earlier it is clear that any delay in road maintenance will not only increase road user cost but ultimately increase road agency cost required for reconstruction of pavement at that stage. Consequences of delayed or untimely maintenance strategies adopted are illustrated in Figure 2.1. Pavement service quality deteriorates rapidly from 'good' to 'poor' in short span if the maintenance and improvement measures are not adopted or delayed. As per MORT&H one-rupee spent on maintenance works saves 2

to 3 rupees in VOC. Also it has been observed that the increase in road agency cost in case of reconstruction or rehabilitation is 4 to 5 times higher than the cost incurred for M & R works. Therefore, if a well-planned and goal oriented pavement maintenance management system is developed during the initial stages of deterioration, pavement condition index shifts from 'poor' to 'good' and can save up to 75% of maintenance costs (Shahin 1994).

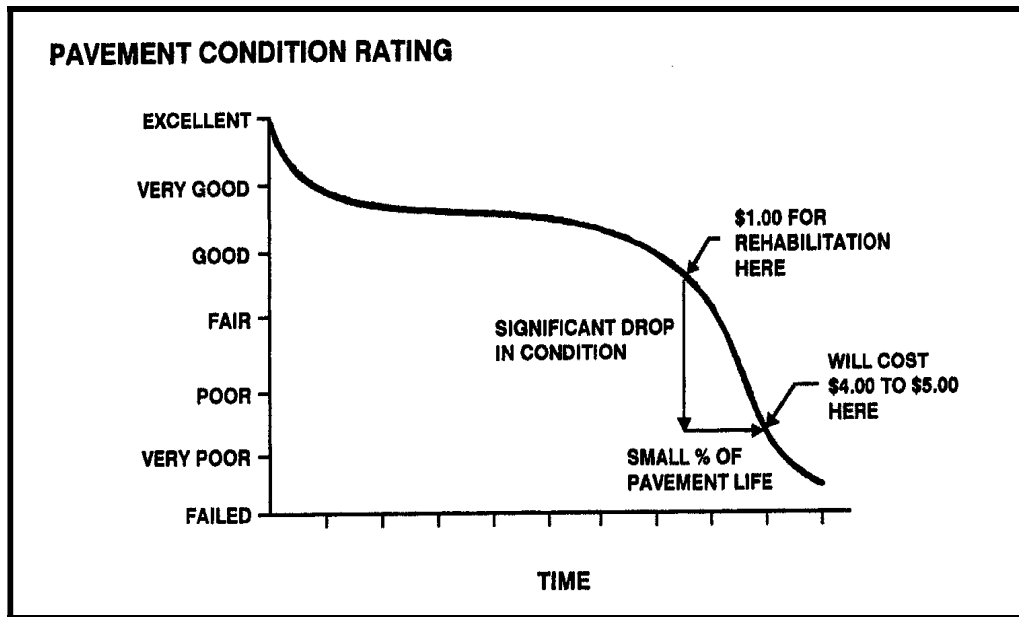


Figure 2.1 Consequences of delay in Maintenance Intervention (Shahin 1994)

2.3 COST MARGINS

Figure 2.2 depicts the effect of maintenance standards on life cycle cost margins. It can be seen from this figure that discounted life cycle costs of operation increase to about 40% in case of no implementation of maintenance works and to 10% in case of reduction in maintenance funds. The maintenance cost incurred by the agency on a good condition road is marginal to around 2% only as compared to road in severely deteriorated condition. Moreover, if due to budget constraint the allocated maintenance funds are reduced, a slight increase of about 10% in VOC is observed due to faster rate of pavement deterioration. If, no maintenance work is carried out the extent of pavement distresses such as cracking and rutting accelerates to a stage after which only reconstruction or rehabilitation is possible and consequently the vehicle operating costs increases by 40% (Robinson 1998).

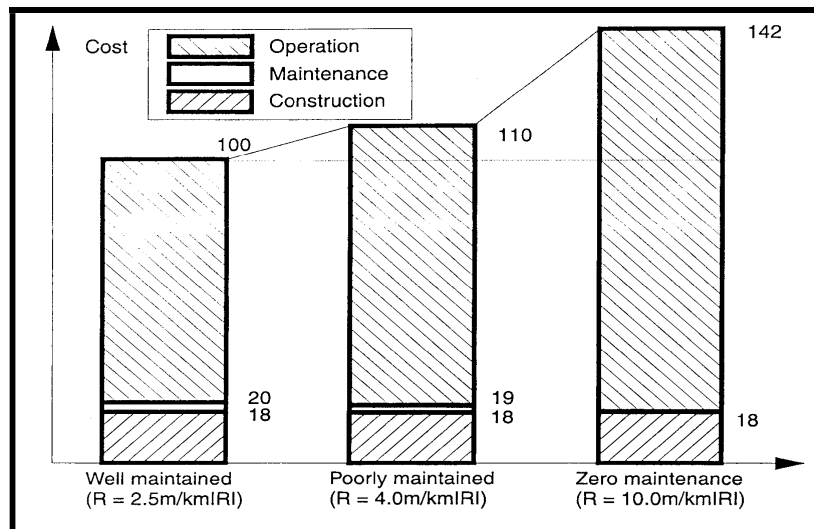


Figure 2.2 Aftermaths of different levels of Pavement Maintenance (Robinson 1998)

2.4 DEVELOPMENT OF RMMS

A systematic highway project appraisal system needs to be adopted for selection of optimum maintenance and rehabilitation strategies within the budget constraint. It should have a strong framework incorporating all the essential parameters required while deciding the best possible alternative for maintenance works. The government should review the existing design, construction and maintenance work standards and update according to the present day's requirements. Also it should focus on future modelling of pavement deterioration based on which best possible maintenance work strategy can be achieved keeping in mind the safety and reliability of road network. Large capital investments in road projects can only be justified if the level of serviceability is maintained for the road users. Road maintenance management system (RMMS) is a HDM-4 based pavement management tool which serves as an appraisal system for assessing the impacts of various maintenance and rehabilitation strategies on pavement service life and gives cost effective decisions. It also gives economic indicators like Road User Cost (RUC), Road Agency Cost (RAC), NPV and EIRR associated with various M&R works based on which the highway engineers can opt for a suitable work strategy within the specified budget. The main objectives of RMMS have been outlined below:

- (i) Forecast pavement deterioration model pertaining to behaviour of pavement distresses viz. cracking, ravelling, rutting, potholing and roughness over the design life.
- (ii) Incorporates a wide range of database related to road network such as road inventory, pavement condition (structural evaluation using scientific techniques), traffic composition and cost associated with various work standards.
- (iii) Budget optimization can be done by evaluating the economic cost of different maintenance and improvement works and adopting the optimum M&R strategy without compromising the road serviceability level.
- (iv) Priority ranking model of different road sections within a road network can be established using RMMS which would govern the road agencies to timely allocate maintenance funds based on the target serviceability levels and works standards.
- (v) Realistic impacts of road maintenance strategies on the life cycle costs and pavement serviceability levels.
- (vi) Helps in better understanding of the relation among maintenance standards, long term pavement performance and road user costs.
- (vii) Predicts the effect of road management policies on the pavement service quality in terms of ridership quality and reliability (convenience and safety) of network system.

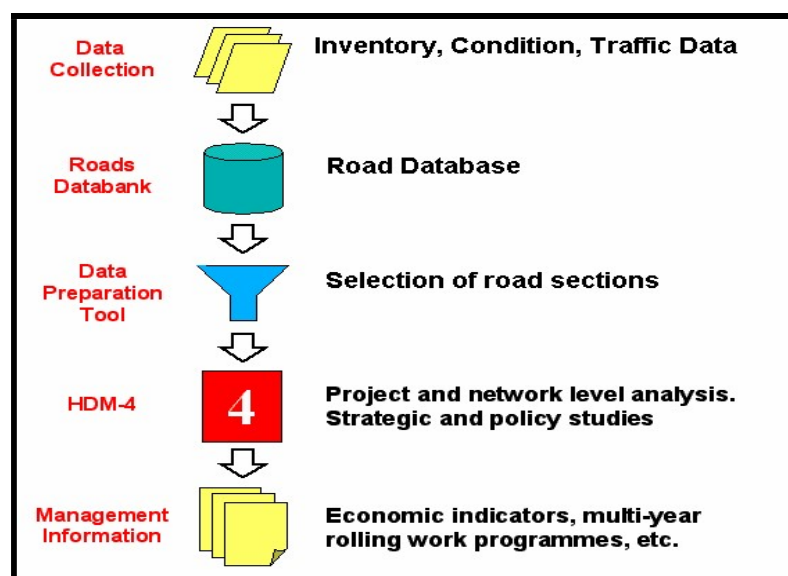


Figure 2.3 Interrelationship between components of HDM-4 based RMMS

2.5 HDM-4 MODEL ARCHITECTURE

The main concept behind implementing HDM-4 model in this study is because it assists the road agencies and other concerned authorities involved in road management and investment alternatives with smart effective pavement conditioning strategies along with optimized economic solutions for the entire pavement life cycle. In the early sixties of 19th century, World Bank developed and tailored it as a strategic pavement management analysis tool dedicated to road projects. Due to its wide range of applicability on various geographical as well as climatic conditions this model has been trending in many countries whenever there is a need of project appraisal system. HDM model is widely recognized computer program among highway engineers owing to its universal acceptance and calibration to local conditions. Based on budget limits it provides the road agencies with effective economic solutions associated to various types of M&R strategies so that there is proper and timely allocation of funds to maintain the pre-defined work standards throughout the pavement design life. Any delay in adopting the maintenance alternatives scheduled by HDM model will degrade the pavement serviceability level and increase the VOC and road agency cost. Figure 2.4 depicts the framework of HDM model including dataset required and analysis tools available to the user.

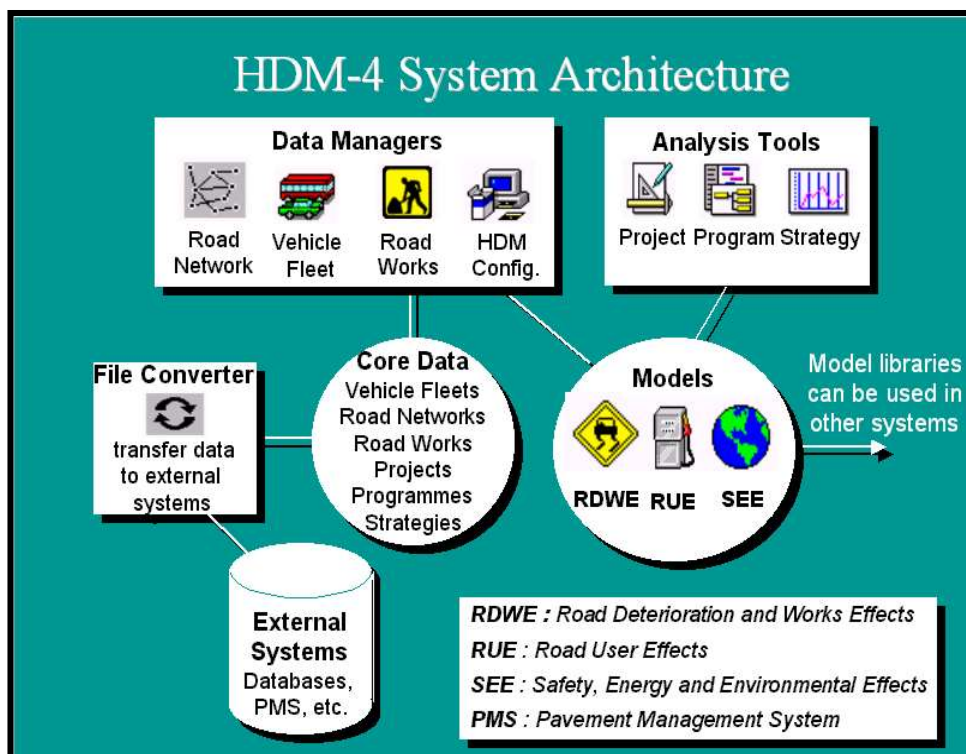


Figure 2.4 Anatomy of HDM-4 (Wightman et al 1999)

2.5.1 Data Manager Models

The dataset required for computational analysis in HDM-4 has the following constituents:

Road Network – For the analysis the foremost data required is the sectional details of network or sub-network which includes the physical attributes like length, width, surface type, category of road, geometry and many other.

Vehicle Fleet – Secondly, we have to define the traffic plying on the above selected road sections. This data constitutes traffic composition, annual traffic growth rates, VOC, TTC and speed limits.

Road Work Standards – It defines both the technical specifications and economical aspects of the various maintenance works and surface treatments to be adopted by the road administration in order to achieve particular level of service. This model incorporates various maintenance work items having some intervention criteria and limits which the road agencies can assign to the network and follow according to their policies.

2.5.2 Technical Models

HDM-4 analytical framework covers the technical analysis of the long term pavement performance throughout its life cycle and incorporates the models described below:

- **Road Deterioration (RD)** – Pavement deterioration primarily occurs with time due to aging of in-service pavement layer materials as a consequence of increment in traffic loading, varying climatic conditions and poor drainage facilities. Therefore, it becomes an integral part of road management to predict pavement deterioration models highlighting the various pavement distresses such as cracking, ravelling, rutting, edge breaks, total damaged area, potholes etc. which the pavement structure has to bear throughout its design life. Based on the severity of these distresses the agency can decide the type and timing of maintenance work intervention. It generates deterioration models for different pavement surface class.
- **Work Effects (WE)** – This program performs a comparative analysis of various maintenance and treatment works adopted for the network on the basis of the effect on the pavement performance year by year in terms of reduction in distresses and the corresponding costs to be incurred. Figure 2.5 depicts the behaviour of pavement in terms of roughness which is considered as one of the

key performance indicators. Each work standard (maintenance works) to be implemented has some intervention criteria which depends on the characteristics of road network system. The expenditure cost to be incurred at the agency's end will depend on the type, level and interval of maintenance works.

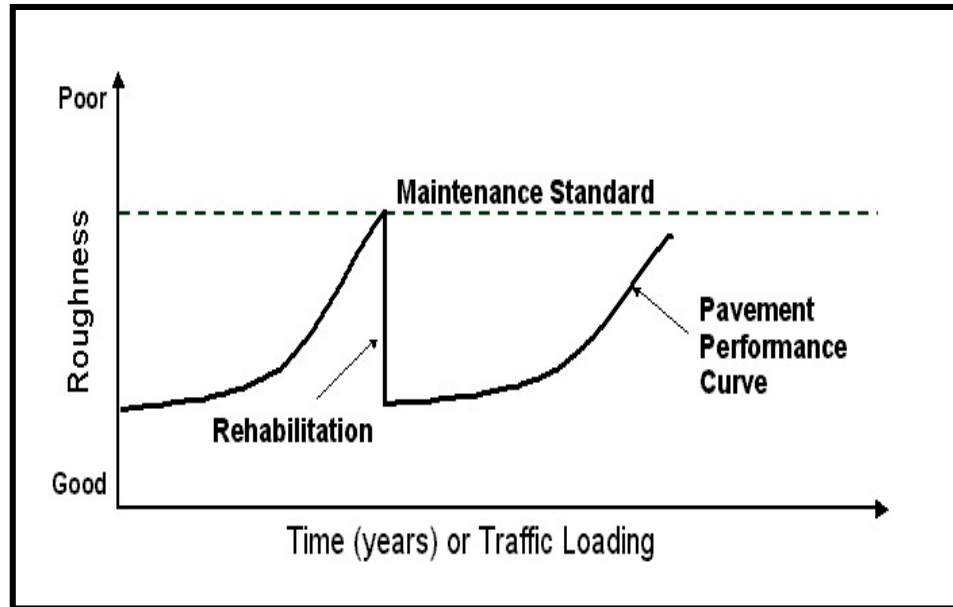


Figure 2.5 Prediction of Long-term Pavement Performance (Odoki and Kerali 2000)

- **Road User Effects (RUE)** – It simulates the impact of improved road condition after the intervention of work standards on the road users in terms of road user costs. This cost model includes the following:
 - (i) Vehicle operation costs (fuel, tyre wear and tear, lubricating and engine oil, vehicle depreciation etc.)
 - (ii) Travel Time Cost (passenger and freight)

2.5.3 Application Modules

The analytical framework of HDM-4 is structured with three main application tools which are described below:

- (i) **Project analysis** – This application is used to check the engineering and/or economic viability of one or more road maintenance and rehabilitation projects based on the concept of life cycle analysis. Economic indicators for adopted maintenance work alternatives can be determined and compared for the

optimization of available budget. Project feasibility can be determined on the basis of following key points:

- Long-term structural monitoring of pavements.
- Pavement deterioration predictions for the life-cycle period.
- Effect of M&R strategies on road user in terms of decrease in VOC and accident costs.
- Economic indicators for selection of optimum M&R strategy.

(ii) **Program analysis** – This is applicable in case a maintenance work plan (year by year) has to be prepared for a whole road network system. It helps the road agencies to develop a priority ranking model having identified road sections and based on NPV/Cost ratio the optimum maintenance works shall be prescribed.

(iii) **Strategy analysis** – This is also another network level application which provides the user with medium to long term budget estimates required for conditioning of different road networks along with the modelling of long term pavement performance and corresponding road user costs. Road networks within the network system can be categorised by several parameters such as surface type, road class, traffic composition, pavement condition etc.

2.6 PAVEMENT CLASSIFICATION SYSTEM

HDM-4 model is based on the concept of “Homogenous Pavement Sections” in which road sections having identical physical characteristics like structural capacity, traffic loading, geometrics and distresses corresponds to homogenous sections. To perform economic analysis for selected road sections it becomes essential to define homogenous sections so that work standards can be assigned accordingly. The road deterioration model incorporated in HDM-4 covers wide range of pavement types. In this study all the selected road sections consist of flexible pavement and Table 2.1 illustrates the various combinations of surface and base layers within the bituminous pavement structure.

Table 2.1 Classification of Flexible Pavements in HDM-4

Pavement Type	Surface Type	Base Type	Description of Pavement Types
AMGB	AM	GB	Asphalt Mix on Granular Base
AMAB	AM	AB	Asphalt Mix on Asphalt (DBM) Base
AMSB	AM	SB	Asphalt Mix on Stabilized Base
AMAP	AM	AP	Asphalt Mix on Asphalt Pavement
STGB	ST	GB	Surface Treatment on Granular Base
STAB	ST	AB	Surface Treatment on Asphalt (DBM) Base
STSB	ST	SB	Surface Treatment on Stabilized Base
STAP	ST	AP	Surface Treatment Asphalt Pavement

Source: Odoki and Kerali (2000)

2.6.1 Pavement Distresses

Under the influence of varying traffic loading and climatic conditions, structural strength of pavement reduces due to development of several distresses over the period of time. These distresses if unattended, rapidly increases and deterioration levels reaches their limiting state. Classification of pavement distresses is based upon identification of distresses through distress survey conducted prior to development of RMMS for the road network. Distress identification approach has been illustrated in Table 2.3. Table 2.2 depicts various types of distresses visible on flexible pavements.

Table 2.2 Standard Flexible Pavement Distresses

Classification	Distress Type
Cracking	Longitudinal, Fatigue, Transverse, Block, Edge
Surface Deformation	Corrugation, Rutting or Plastic deformation
Surface Deterioration	Ravelling, Potholes, Patching
Surface Defects	Bleeding, Segregation

HDM-4 tool consist of inbuilt distress models which have been briefly discussed below:

Cracking – This type of distress occurs due to fatigue caused by repeated traffic loading and ageing of layer materials over a period of time. Crack propagation through the pavement structure can severely damage the structural condition of pavement layers. In HDM-4 cracking has been classified in the following types:

- (i) **Structural cracking** – Its occurrence is related to traffic and environmental conditions and can be observed on-site having crack width of 1-3 mm or more. Various types of structural cracking are longitudinal, map or alligator and block cracking depending upon the pattern of crack propagation.
- (ii) **Transverse thermal cracking** – This type of cracking mainly occurs due to thermal stresses generated because of significant temperature variations and seasonal variations.

Ravelling - The loss of pavement material due to traffic loading and weathering leads to ravelling. It is progressive in nature and is prominent in thin bituminous pavements and poorly constructed pavements with low quality design mix. Ravelling initiation occurs on a road pavement section when 0.5% of total paved area has been affected by these distresses.

Potholing – Potholes are cavities on pavement surface which usually develop after cracking or ravelling distresses occur. These damage the pavement structure as water accumulation leads to stripping of materials, de-bonding of layers, crack propagation and lower the strength of layer materials. A cavity on surface having a minimum diameter of 150mm and depth 25mm is marked as pothole. It is expressed in number of potholes (unit area of 0.1 m²) per kilometre.

Rutting – It is defined as the permanent or plastic deformation which occurs due to excessive strains within base layers which leads to formation of ruts or depression along the wheel path. The severity of this distress will depend whether it's a surface failure and/or subgrade failure. Rut depth is measured on the road surface with a straight edge and the modelling is performed in HDM-4 after all other distress models (i.e. ravelling, cracking, potholing) have been analysed.

Roughness – It is the most vital parameter in establishing deterioration models. Roughness represents the vertical undulations or unevenness caused on road surface due

to repeated traffic loading. It is an indicator of the ridership quality and hence plays a crucial role in economic analysis specifically to determine road user costs like VOC. It is measured using fifth wheel bump integrator (Roughometer) in the direction of traffic which gives road roughness in terms of Unevenness Index. Roughness model comprises of various components viz. structural, cracking, rutting, potholing and environmental.

Edge-break – This type of pavement condition is observed on narrow roads having unpaved shoulders, where shear failure leads to chipping of pavement edge and loss of surface and base layer materials. Edge break model in HDM-4 is predicted only for road pavements of width less than 7.5 meters.

Table 2.3 Distress Measurement Approach

Pavement Distresses	Definition
Area of distress	Sum of rectangular areas circumscribing manifested distress as a percentage of the carriageway area
Narrow cracking	Interconnected or line cracks of 1-3 mm crack width
Wide cracking	Interconnected or line cracks of 3 mm crack width or greater
Indexed cracking	Normalised sum of narrow and wide cracking
Transverse thermal cracking	Unconnected cracks running across the pavement
Ravelling	Loss of material from wearing surface (sq. meter area)
Pothole	Open cavity in the road surface with at least 150 mm diameter and at least 25 mm depth
Edge-break	Loss of bituminous surface material from the edge of pavement
Rut-depth	Maximum depth under 2 m straight edge placed transversely across a wheel path
International Roughness Index (IRI)	Reference measure expressing roughness as average rectified slope statistic of the longitudinal profile of pavement
Mean Texture Depth	The average depth of the road surfacing determined from sand-patch test
Skid resistance	Resistance to skidding expressed by the sideways force coefficient (SFC) using SCRIM

Source: Morosiuk et al. (2001)

CHAPTER - 3

LITERATURE REVIEW

3.1 STUDIES CONDUCTED IN INDIA

Shah et al. (1997) introduced the concept of pavement “serviceability” as quantitative assessment of pavement service life in context to road infrastructure development and preservation. Present serviceability index (PSI) and Roughness Index (IRI) should be adopted as performance indicators in terms of level of service and ridership quality. Study area includes urban roads network located in Noida city, India. Study reveals the relationship modelled between pavement quality levels and roughness. PSI model represents pavement age as its function. Calibration of AASHTO prediction equation for PSI to Indian conditions has been done in order to assess the applicability for urban roads of India. Based on these validated models maintenance strategy has been laid out for future pavement management and preservation of urban roads.

Aggarwal S. et al. (2004) HDM-4 computer program has been used to develop distress models for National Highways network comprising of twenty-two road pavement sections in the territory of UP (Uttar Pradesh) and UK (Uttarakhand). Comparison of various M&R strategies has been done on the status of economic indicators viz. NPV and IRR and optimal maintenance solution determined under constrained budget scenario. It has been observed that roughness progresses from 3.2 to 4.4 m/km IRI when the available funds are reduced to 50%.

Gupta et al. (2011) developed road deterioration model using ANN and statistical analysis tool for rural road network consisting of 18 road sections in the state of western UP and UK. Regression analysis has been carried out to generate pavement deflection and roughness prediction model. Efficacy of these models have been determined by validating the model using student’s T-Test. Study concludes that ANN model gives better and realistic results in terms of fitness parameter R^2 . Priority ranking index of order in which the cost effective maintenance work has to be assigned was established for the candidate road sections. Prioritization of road network will assist the road administration in proper and timely allocation of funds for the proposed road works scheme.

Jain et al. (2012) conducted comparative analysis of economic benefits associated with different types of M&R strategies mainly condition responsive and scheduled type. Study area includes 8 homogenous sub-sections of NH-24 (Ghaziabad-Hapur) road network. Maintenance work standards include condition responsive overlay and scheduled overlay. Results derived from economic analysis (NPV\CAP ratio) clearly indicate that scheduled overlay gets triggered at an early stage as compared to condition responsive and therefore the frequency of intervention is higher for the former.

Jain et al. (2013) examined the various control parameters for the identification of optimum road maintenance plan for high volume roads. Dataset comprises of road physical attributes of one National Highway (NH-24 Ghaziabad to Hapur) and one Expressway. Using the concept of Homogenous test sections, NH and Expressway have been divided into five and eight sub-sections respectively. Homogeneity of these sub-sections is based on similarity of climatic conditions and geometrics but vary in terms of traffic composition and pavement conditions. Pavement condition survey has been carried out to congregate data related to surface distresses and other physical characteristics such as lane width, length of sections and drainage conditions. Vehicle fleet model incorporates traffic volume (AADT) and initial composition in analysis using HDM-4. To determine the optimum road works strategy various work alternatives as shown in Table 3.1 have been proposed to target the serviceability levels of the road network.

Table 3.1 Maintenance Strategies assigned to Road Network

Work Standards	Description of work activities/operations
Base Alternative	(Crack + ravel + pothole) patching
Alternative 1	Resealing with SDBC 25 mm
Alternative 2	Overlay with 40 mm BC
Alternative 3	Resealing with 25 mm SDBC & Overlay of 40 mm BC
Alternative 4	Strengthening with 50 mm DBM & 40 mm BC

Chandra S. et al. (2013) compared regression model with ANN model by developing a mathematical relation between pavement distress parameters and roughness. Distress data has been gathered using NSV which constitutes the distress parameters of four

National Highways of India. Quantitative assessment of the two models has been done on basis of predictions of roughness values for given distress parameters. The candidate road sections are two-lane flexible road pavements of carriageway width 7.5 m. Results indicate that ANN model gives more realistic roughness prediction than regression model. It has been observed that addition of distress parameters reduces the performance of Regression model.

Sandra A.K. et al. (2013) developed multi-linear regression model to understand the interaction between road roughness IRI and prominent pavement distresses such as potholes, ravelling, patching, cracking and rutting on Indian roads using SPSS software program. Study area comprises of different categories of roads viz. (NH) National highways, State highways (SH) and (MDR) Major district roads having total road length of 39.5 km in the state of Rajasthan. Pavement distress data has been congregated by dividing the road stretch into 395 sections of length 100 m each. Severity and extent of pavement distresses have been measured and levels designated as low, medium and high. Study concludes that roughness progression significantly varies with the extent and level of distresses within the pavement structure. Regression model obtained using SPSS has high adequacy in terms of R^2 of value 0.986 which shows a strong correlation between roughness and distresses. Validation of the model has been done by comparing the observed roughness values (10% of total observed values) with the predicted values given by multi-linear regression equation on 40 road stretches. Patching and potholes also contribute significantly towards roughness progression and should be targeted while planning a road maintenance program.

Shah et al. (2013) developed a methodology to formulate OPCI applicable to urban road conditions. Study is subjected to 10 urban road sections with total road length of 29.92 km with four and six lane divided carriageway. Pavement distresses have been measured with various pavement evaluation techniques pertinent to both structural and functional assessment. OPCI constitutes all the key distresses developed individually (PCI; distress, roughness, structural capacity and skid resistance).

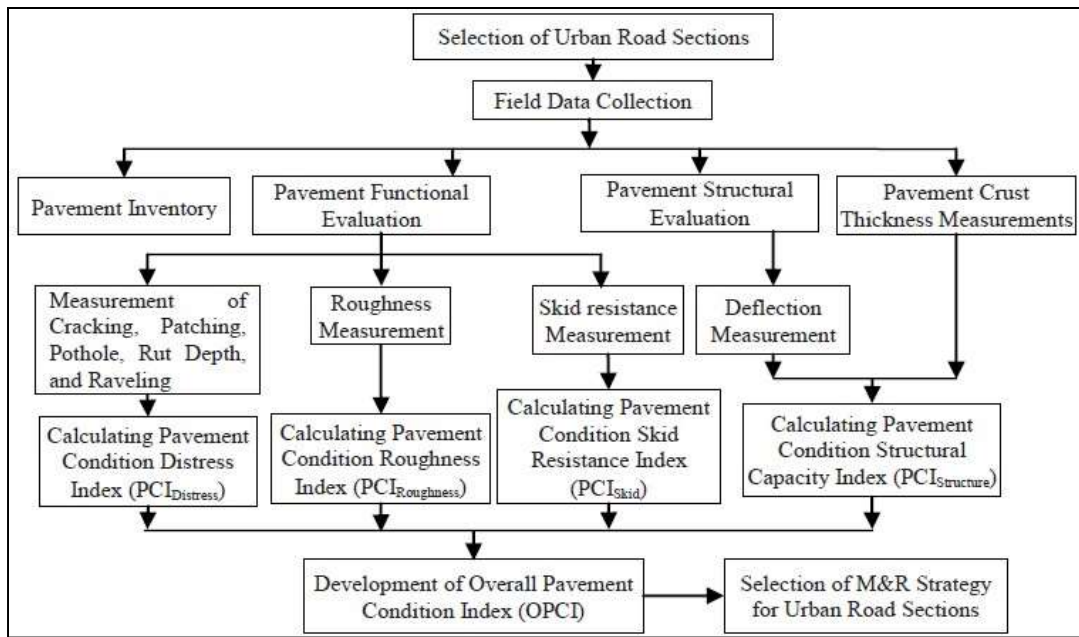


Figure 3.1 Hierarchy of OCPI

The main objective of OPCI is to scientifically evaluate the existing pavement condition and quantify the optimal road maintenance strategy applicable for the selected road sections. Results suggested different road treatment works for various sections.

Thube D.T. (2013) developed road maintenance strategy using HDM4 deterioration models for rural road network of India. Pavement distresses noticeable in low-volume roads i.e. cracking, ravelling, potholes and edge break have been considered in the present study. Calibration of in-built HDM4 models to Indian conditions have been done using “window monitoring technique”. Statistical calibration program developed in ‘Visual C’ language has been adopted for calibration of models. Validation of models have been done on the basis of fitness measures of R^2 and RMSE. The study concludes that the efficacy and reliability of HDM-4 model depends upon the selection of precise and well defined calibration coefficients so as to develop a realistic and effective technical and economic appraisal system pertaining to local conditions.

K. SurendraKumar et al. (2013) developed prediction models using Markov application for twenty pavement sections. Future modelling of pavement service life has been carried out using transition probability matrix. Mathematical modelling based on Markovian concept has been done to quantify pavement deterioration and the parameters involved. Using Poisson’s distribution approach, single step transition

matrix has been formulated and sequential transition matrices calculated for future modelling of pavement performance under the given set of conditions.

Girimath et al. (2014) identified optimum M&R strategy for Bangalore city using HDM4 model. Dataset comprises of pavement condition survey of identified 12 road sections located at the periphery of the city. Priority ranking model of road sections has been developed by comparing the economic indicators NPV/Cost ratio of optimum maintenance work alternative identified for the road network. From the various maintenance alternatives proposed, bituminous overlay (BC) 40mm has been found as optimum maintenance solution. All the proposed alternatives were assigned to the road network and compared in terms of economic benefits. Study concludes that HDM4 is a powerful pavement management tool to predict the best possible road management strategy with economic solutions such as budget optimization and prioritization to accomplish the pre-defined serviceability levels.

Mathew B.S. et al. (2014) performed genetic algorithm (GA) based analysis to develop optimal road maintenance program for rural roads (low traffic volume) in the state of Kerala. Primary objectives to be accomplished by this deterministic model were to enhance the pavement performance by delaying deterioration and achieve desired levels of service at minimal expenditure costs. Road network consists of 15 road sections with length 0.5 km. Pavement performance of rural road network has been measured in terms of pavement condition index (PCI). Scientific PMMS has been developed and optimised using GA for timely and proper allocation of available maintenance funds to implement the optimum M&R strategy identified for the road network. Results indicate that optimistic model developed is versatile in nature as it incorporates both functional and structural performance parameters.

Deori S. et al. (2016) developed PMMS using HDM-4 model for National Highway network and calibrated it to local Indian condition. Data acquired for the modelling includes road inventory data and pavement condition data pertinent to twenty-three National Highway road sections for successive period of three years. Road maintenance work standards have been proposed to forecast trend of pavement deterioration using life-cycle analysis approach. Calibration factors for various distress models have been obtained under the effect of varying traffic conditions, pavement composition and climatic conditions for candidate road pavement sections. To obtain more realistic and

accurate calibration coefficients the road network system has been categorised into six Homogenous test sections and consequently the calibration results have been analysed. Efficacy and reliability of calibrated distress models have been done using statistical evaluation technique i.e. Chi Sq. test.

Chopra T. et al. (2017) developed five prediction models (cracking pattern, ravelling pattern, pothole pattern, rutting pattern and roughness pattern) pertaining to pavement distresses for 16 road sections within urban road network using Genetic Programming (GP) system. Dataset consists of physical characteristics of 16 identified road sections for the year 2012-2015. The road sections are mostly divided carriageway with pavement width of 6 m to 11.80 m and section length varying from 0.80 m to 2.70 m. The results obtained show high adequacy of pavement distress prediction as GP has developed a realistic correlation between predicted values and observed values. Validation of distress models have been done through fitness measures of R² and RMSE. GP model is applicable for urban road networks falling under similar geographical and climatic conditions as of Patiala city with traffic loading in the range of 0.1 to 0.85 msa and pavement strength MSN in the range of 2 to 4.5.

Figure 3.2 Distress Models obtained from GP for Urban Roads

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>

Chopra T. et al. (2017) developed pavement distress model using HDM-4 program and calibrated it to the local conditions of Patiala city having 4 urban road sections. Majority of road sections are two lane with pavement width ranging from 6m to 9m. Various road maintenance works have been proposed and assigned to road network to predict the effect of road works on progression of pavement distresses with time. Most favourable

road maintenance strategy has been determined by comparing the economic benefits of various work alternatives in terms of cost benefits to road users and road agencies. On the basis of economic index of NPV and IRR it has been concluded condition responsive M&R strategy is far more economical than scheduled M&R strategy and hence is preferable in case of budget constraint.

Chopra T. et al. (2017) carried extensive research related to strategic road management solutions for urban road network. Four urban road sections viz. Passey road, Ghuman road, Bhupindra road and Bhadson road have been identified to develop PMMS. Each of the road sections have a length of 1 km with pavement width in the range of 7 m to 9 m. Economic analysis has been conducted to determine the optimum road management strategy by comparing economic benefits associated with various maintenance work alternatives. On the basis of Net Present value (NPV)/cost ratio it has been determined that road agencies should prefer condition responsive strategy to scheduled strategy owing to its economical range.

3.2 STUDIES CONDUCTED IN ABROAD

Edward et al. (1995) studied the relationship between roughness and the factors which influence its progression for flexible road pavements and developed a roughness prediction model. Observed field data has been gathered to predict roughness increment using progressive algorithm along with certain control parameters. Study area comprises of flexible pavements in Ghana, West Africa having granular bases underlying bituminous surfaces. Dataset covers wide range of traffic loads plying on major primary and secondary roads. Study concludes that environmental conditions and pavement strength significantly contribute towards acceleration of roughness. Pavement structural capacity has a greater impact on roughness progression than traffic loading. It is suggested to frame realistic deterioration models predictive in nature for future preservation of pavement service life while planning of maintenance strategy. Timely intervention of optimum M&R strategy will retard rate of roughness progression.

Fwa F. T. et al. (2000) discussed the approach of solving problems of PMMS oriented to multi-objective Network level with the application of genetic algorithm (GA). Multi-objective (two-three) optimization analysis has been done by implementation of GA. An optimum solution set has been adopted introduced by Pareto (1848-1923). Multi-objective programming tool derived from this study is an advancement to overcome the

shortcomings of present pavement management tools which support only single objective optimization.

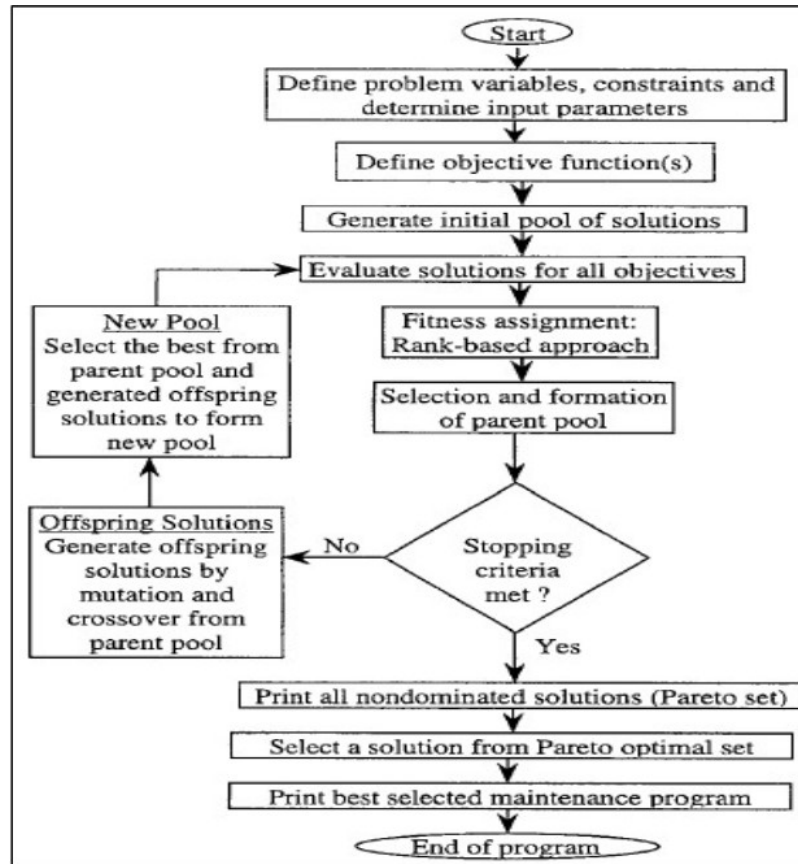


Figure 3.3 Multi-Objective Optimization using Genetic Algorithm Tool

Liu. (2006) studied and analysed thoroughly the road network system in China. Due to vast road network of over 1,900,000 km roads laid across the entire nation, a management strategy had to be structured for future monitoring of road network. The road network constitutes 40,000 km of expressways and another 15,000 expressways have been targeted for completion by 2010. China introduced PMS first in 1984 and since then huge advancements have been made in terms of development of effective road management plan. Implementation of PMS is not on a large scale in China as its road administration has been more active towards road construction.

Khan M.U. et al. (2010) suggested optimal pavement management solutions using HDM-4 model with an objective to assist the road administration of Bangladesh with an efficient road network maintenance strategy. Road networks under the jurisdiction of Road & Highways department (RHD) has been divided into 48 groups on the basis of road attributes such as traffic composition, lane width, surface type and optimum

maintenance standard defined for individual road group. Different maintenance standards have been proposed for a road group and based upon the economic indicator NPV/Cost ratio, optimum work standard has been determined. To determine optimum maintenance intervention criteria, three intervention levels have been adopted and assigned to each road group and comparison of NPV values has been done to define the optimum work intervention criteria.

Niaraki M.L.R et al. (2011) developed PMMS using GIS integrated Dynamic segmentation (DS) technique for Iraq road network. The main objective of this study was to assist the highway engineers with more effective decision making of road management strategies. Road maintenance data model has been designed with high precision, accuracy to simulate actual ground conditions and takes into account various significant road network parameters. DS technique assigns each road section a link and segregates network links on the basis of heterogeneous attributes of road network. With the integration of GIS, data model stored in DS can be displayed on maps. The old segments on the network links can be automatically updated on the basis of spatial relation. Run time for automatic upgradation varies from 0.2 to 0.4 seconds which is way much faster than the manual one which consumes 15 to 62 seconds.

Jorge D. et al. (2012) proposed an optimized pavement maintenance system called GENPAV-HDM-4 to provide smart pavement management solutions targeting both periodic as well as routine maintenance strategies for the road network. According to the recent amendments in Portuguese legislations there arises a need to update the existing road management plan. Pavement visual survey has been conducted for 67 urban road sections of total road length of 141.2 km situated in the city Viseu, Portugal and performance models have been established for each section. The existing PMS has optimization system (MOS) which follows AASHTO prediction model has been replaced by HDM4 model in the new optimized management tool (GENPAV HDM-4). The updated MOS is based on the concept of homogenous road sections in terms of pavement condition, traffic and climate conditions. Study concludes that the new MOS will serve the municipal road administration as a powerful road appraisal system.

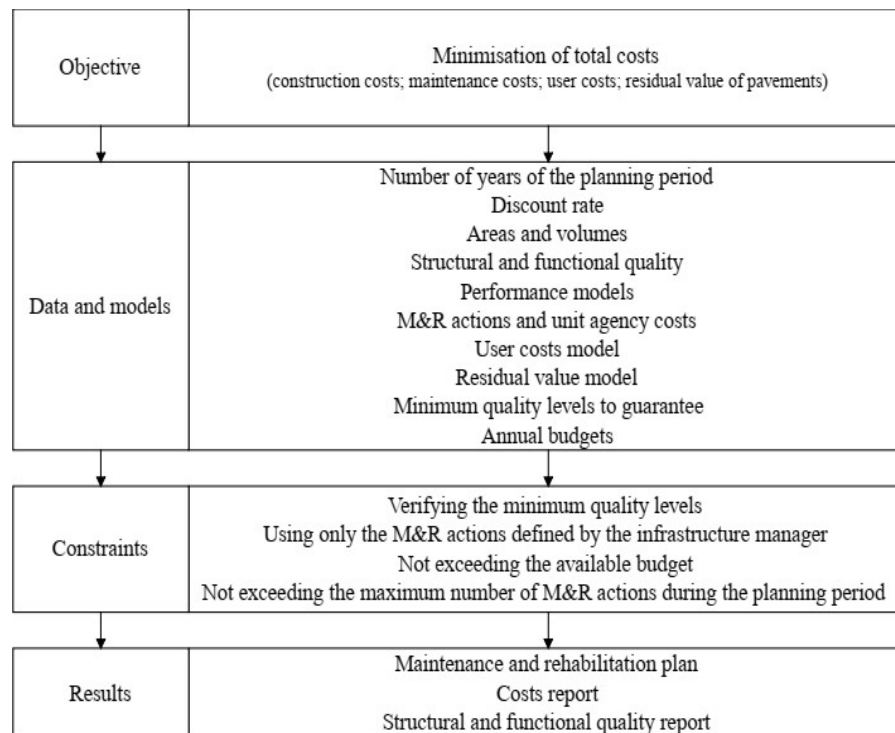


Figure 3.4 MOS components

Msallam M. et al. (2014) discussed about the pros and cons of existing pavement management system curated by Ministry of Public Works & Housing (MPWH) of Jordan. In the last decade the road administration has focused on development and expansion of road network and has diverted 76% of allocated funds on road construction. The present total road length tolls to 8200 km and has been expanding at a remarkable pace. Road financial budget for maintenance works has been hiked to 24%. Currently the framework of PMS adopted by MPW&H relies on distress evaluation only and does not account for the impact of structural evaluation parameters for efficient pavement rating system. Pavement serviceability index has been upgraded and refined with the addition of new rating criterion for more reliable road management system within the economical range.

Kerali et al. (2016) discussed about the architecture of HDM software and analogy of its analytical framework. It serves as a pavement management tool to road administration and highway engineers involved in technical and economic appraisal of road maintenance projects. The salient features of HDM4 model provides the user with handful of road appraisal options applicable for different project scenario. Prediction of long term performance models, budget optimization and prioritization of optimum maintenance solutions to various road projects are the utilities of HDM. Study focuses

on calibration of HDM models to the local conditions to accurately predict future distresses. HDM predicts pavement behaviour under given set of conditions for the analysis period.

Saha P. et al. (2017) Markovian technique has been implemented to develop probabilistic pavement deterioration models applicable for low-volume roads in Colorado. Previous maintenance work records have been gathered by CDOT for a period of 5 years from 2012-2014. Road network comprises of 116 roads covering a stretch of 2,022 miles. These low volume roads have been categorised into 342 segments by CDOT. The case study revolves around the probabilistic approach to develop deterioration prediction models separately for five key distress indices viz. longitudinal cracking index, transverse cracking index, fatigue cracking index, rutting index, roughness index and ridership index for the selected road segments. Study suggests that probabilistic approach should be preferred to deterministic approach as the former incorporates uncertainty factors of varying traffic loading and climatic conditions which greatly affect the pavement performance. Regression equations for all the deterioration models have been developed using the mean extracted from probability distribution matrices. Markov distress models contain pavement age as the only variable. Results indicate gradual deterioration of longitudinal, fatigue and rut indices as compared to transverse and ridership indices over the years.

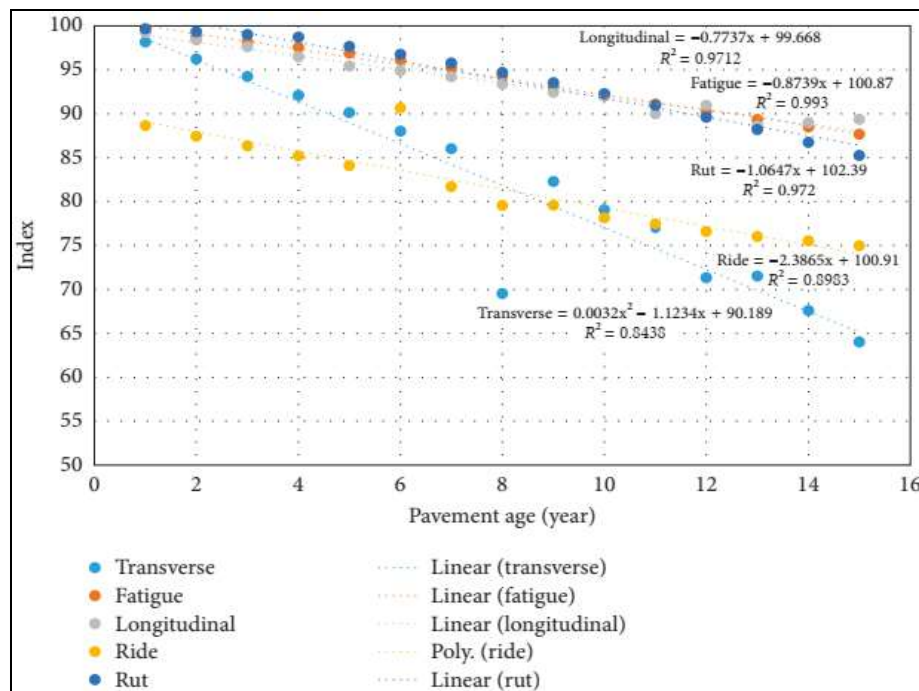


Figure 3.5 Markov Deterioration Models

CHAPTER - 4

DEVELOPMENT OF RMMS USING HDM-4 MODEL

4.1 GENERAL

In this study RMMS has been developed using HDM-4 model for National Highways road network across various geographical locations in India to analyse and prepare road management scheme for analysis period of 20 years. Road condition data has been acquired from literature survey and government publications. Development of RMMS is a hierarchical process which requires a systematic methodology and the modelling has been performed using HDM-4 tool.

4.2 DATA ACQUISITION

The first step in the computational procedure is identification and selection of road sections for which the optimum M&R strategies need to be determined along with economic benefits. All the selected 29 road pavement sections of NH network fall under various geographical and climatic conditions. These road sections are homogenous in nature in terms of identical physical characteristics. Table 4.1 shows the sectional details with unique ID assigned to selected road sections.

Table 4.1 Sectional Details

S. No.	Sections	Description	Road Classification	Length (km)
1	NE-1GJ01	Ahmadabad-Vadodhara	Expressway	1
2	NE-1GJ02	Vadodhara-Ahmadabad	Expressway	1
3	NE-1GJ03	Ahmadabad-Vadodhara	Expressway	1
4	NE-1GJ04	Vadodhara-Ahmadabad	Expressway	1
5	NH-14GJ05	Radhanpur-Deesa	National Highway	1
6	NH-2UP01	Allahabad-Khaga	National Highway	1
7	NH-2UP02	Allahabad-Varanasi	National Highway	1
8	NH-37AS01	Nagaon-Guwahati	National Highway	1
9	NH-4KA01	Tumkur-banglore	National Highway	1
10	NH-4KA02	Dharwad-belgaon	National Highway	1
11	NH-4KA03	Tumkur-sira	National Highway	1

12	NH-5AP01	Vizag–Srikakuram	National Highway	1
13	NH-5AP02	Vizag–Srikakuram	National Highway	1
14	NH-5AP03	NH-5-vizag port	National Highway	0.5
15	NH-5AP04	NH-5-vizag port	National Highway	0.5
16	NH-4MH01	Maharashtra border-belgaon	National Highway	1
17	NH-7MH02	Hyderabad-nagpur	National Highway	2.5
18	NH-7MH03	Hyderabad-nagpur	National Highway	0.5
19	NH-73 01	Roorkee-Saharanpur	National Highway	11
20	NH-73 02	Roorkee-Saharanpur	National Highway	14
21	NH-73 03	Roorkee-Saharanpur	National Highway	10
22	NH-73 04	Roorkee-Saharanpur	National Highway	12
23	NH-74 01	Haridwar-Najibabad	National Highway	13
24	NH-74 02	Haridwar-Najibabad	National Highway	17
25	NH-72 01	Poanta Sahib-Dehradun	National Highway	13
26	NH-72 02	Poanta Sahib-Dehradun	National Highway	14
27	NH-72 03	Poanta Sahib-Dehradun	National Highway	16
28	NH-72 04	Poanta Sahib-Dehradun	National Highway	18
29	NH-72 05	Poanta Sahib-Dehradun	National Highway	17

4.3 PROPOSED METHODOLOGY

The fundamental concept behind an adequate and reliable RMMS is to calibrate accurately the in-built distress models in HMD-4 to the existing local conditions. If, the calibration factors related with distress models are not configured precisely then due to large variation in predicted and observed distress behaviour, deterioration model obtained will be unable to simulate more realistic local conditions. The default values of calibration factors of in-built distress models in HDM equals to unity. In this study calibration factors have been carefully scrutinized from past research works before development of RMMS for the selected NH network. Chopra et al. determined calibration coefficients for NH road networks identical to physical attributes and environmental conditions of selected road sections and therefore have been considered in the present study. Calibration coefficients adopted in the research study are 2.4, 0.6, 0.4, 0.4 for cracking distress, ravelling distress, rutting distress and roughness distress respectively. Validation of distress models developed using HMD-4 has been performed by simply comparing the similarity between the predicted values (given by HDM-4

model) and observed values (field survey data) to check the applicability and adequacy of the model for the specified conditions. This study also covers the economic parameter by determining the optimum road maintenance & rehabilitation strategy on the basis of maximum NPV to cost ratio.

Table 4.2 depicts field data pertaining to identified NH road sections showing various road physical characteristics.

Table 4.2 Road Section Attributes

Section name	Description	Pavement age (years)	AADT	Surface type	Surface Thickness (mm)	Roughness (m/km) 2011	Cracking (%)	Ravelling (%)	Potholes (No./km)	Rutting (mm)	BBD (mm)
NE-1GJ01	Ahmadabad-Vadodhara	8	8387	BC	50	2.3	2	2.3	0	2.2	0.49
NE-1GJ02	Vadodhara-Ahmadabad	8	8304	BC	50	2.5	7	5	0	3.5	0.37
NE-1GJ03	Ahmadabad-Vadodhara	8	8387	BC	50	2.5	1	1	0	2.7	0.24
NE-1GJ04	Vadodhara-Ahmadabad	8	8304	BC	50	2.5	1.5	1	0	2.2	0.35
NH-14GJ05	Radhanpur-Deesa	3	3715	BC	50	2.7	27.07	23	3	2.4	0.56
NH-2UP01	Allahabad-Khaga	6	4789	BC	50	2.5	7	4	2	3	0.55
NH-2UP02	Allahabad-Varanasi	6	4906	BC	50	2.8	1	2	0	2.7	0.67
NH-37AS01	Nagaon-Guwahati	1	4316	BC	40	2.5	0	0	0	2	0.64
NH-4KA01	tumkur-banglore	8	16789	BC	40	3.2	4.57	2	0	2.6	0.75
NH-4KA02	dharwad-belgaon	3	5088	BC	40	3.7	5	2	0	2.1	0.7
NH-4KA03	tumkur-sira	7	11456	BC	40	3.9	19.86	15	2	3.6	0.75
NH-4MH01	mahrastra.border-belgaon	7	5029	BC	40	3	0	0	0	2.1	0.8
NH-5AP01	Vizag-Srikakuram	7	6771	BC	50	2.5	1.16	0	0	1.6	0.68
NH-5AP02	Vizag-Srikakuram	7	6771	BC	50	2.8	0.66	0	0	2.7	0.75
NH-5AP03	NH-5-vizag port	5	5682	BC	50	2.9	10.87	8	1	1.9	0.72
NH-5AP04	NH-5-vizag port	5	5682	BC	50	2.9	11	9	1	1.7	0.88
NH-7MH02	hyderabad-nagpur	3	4288	BC	40	2.5	0	0	0	2	0.75
NH-7MH03	hyderabad-nagpur	3	4288	BC	50	2.4	0	1	1	2	0.65
NH-73 01	Roorkee-Saharanpur	9	7840	AC	25	3.6	4	5	1	7	0.65
NH-73 02	Roorkee-Saharanpur	7	7750	AC	25	2.4	1	1	0	2	0.8
NH-73 03	Roorkee-Saharanpur	9	7670	DBSD	25	6.9	15	10	10	8	1.02
NH-73 04	Roorkee-Saharanpur	9	7650	DBSD	25	6.3	10	7	3	7	0.95
NH-74 01	Haridwar-Najibabad	9	5480	DBSD	25	4.5	6	5	1	7	0.95
NH-74 02	Haridwar-Najibabad	9	5520	DBSD	25	4.7	5	4	3	6	1.1
NH-72 01	Poanta Sahib-Dehradun	11	3650	SBSD	15	5.9	7	10	0	5	0.85
NH-72 02	Poanta Sahib-Dehradun	9	5720	AC	25	5.1	10	5	2	8	0.7
NH-72 03	Poanta Sahib-Dehradun	9	5870	AC	25	5.7	12	5	2	6	0.75
NH-72 04	Poanta Sahib-Dehradun	11	7280	DBSD	25	5.2	10	8	1	10	0.9
NH-72 05	Poanta Sahib-Dehradun	11	6840	DBSD	25	6.2	12	9	2	9	0.68

4.4 INCORPORATION OF DATA MODELS

As discussed earlier HDM-4 consists of three data models viz. road network, vehicle fleet and work standards which needs to be inputted before performing the analysis. Input data related to the road network for which the road management system has to be established using HDM4 model has been depicted in Table 4.3.

Table 4.3 Data Survey Index

Type	Constituents
Road Inventory	Length of section, carriageway width, surface type, speed flow type
Pavement History	last year of resurfacing, reconstruction and/or preventive treatment, pavement age
Pavement Condition	surface distresses, drainage, geometrics
Traffic Data	AADT, type and composition of commercial vehicles
Climatic conditions	Climate zones, Temperature range

The sequential manner in which data has been incorporated in HDM-4 has been illustrated from Figure 4.1 to Figure 4.13. Figure 4.1 represents the road network model having various parameters related to different road sections.

Figure 4.1 Sectional Details

Figure 4.2 shows pavement history i.e. record of any previous repair or maintenance works along with structural details of pavement (thickness and SNP).

Figure 4.2 Pavement Historical Data and Structural Details

Figure 4.3 illustrates the observed values of various distress parameters obtained from field survey

Condition at end of year	2011
Roughness (IRI - m/km)	2.50
Total area of cracking (%)	1.00
Ravelled area (%)	1.00
Number of Potholes (No./km)	0.00
Edge break area (m ² /km)	10.00
Mean rut depth (mm)	2.70
Texture depth (mm)	0.50
Skid resistance (SCRIM 50km/h)	0.40
Drainage	Fair

Figure 4.3 Pavement Condition Catalogue Showing various Distress Parameters

Figure 4.4 represents calibration factors for initiation and progression of cracking model, pothole model and ravelling model

Calibration factors	Initiation	Progression
All structural cracking:	1	2.4
Wide structural cracking:	1	1
Transverse thermal cracking:	1	1
Ravelling:	1	0.6
Pothole:	1	1
Edge break:	1	

Distribution of cracking	Value	Unit
All structural cracking:	100	%
Transverse thermal cracking:	0	%
Total:	100	%
Wide structural cracking as a percentage of All structural cracking:	0	%

Surface Distress Retardation	Value	Unit
Cracking retardation time:	0	years
Ravelling retardation factor:	1	

Figure 4.4 Calibration Factors for Surface Distress

Figure 4.5 represents calibration factors required for rutting model and roughness model

Rutting	Value
Initial densification:	0.4
Structural deterioration:	1
Plastic deformation:	0
Surface wear:	1
% vehicles with studded tyres:	0
Is salt used on the road:	no

Structural Number	Value
Seasonal effects:	1
Structural no. due to cracking:	1

Roughness	Value
Environmental coefficient:	1
Progression:	0.4

Others	Value
Effective number of lanes:	4

Figure 4.5 Calibration Factors for Structural Defects

4.5 VEHICLE FLEET DATA MANAGER

This model manages the traffic composition along with economic parameters based on the traffic survey data reports for the identified road network. In this study the basic vehicle attributes and related economic costs (VOC) of motorized traffic have been

defined in the vehicle fleet model. Five different categories of motorized vehicles viz. articulated trucks, heavy trucks, LCV, cars (medium size) and buses (medium size) have been selected and their physical characteristics, VOC, percentage composition and annual growth rates defined for the NH road network.

Figure 4.6 depicts the vehicular characteristics of selected motorized vehicle.

The screenshot shows a dialog box titled "Vehicle Attributes: heavy truck" with three tabs: "Definition", "Basic Characteristics", and "Economic Unit Costs". The "Basic Characteristics" tab is active. It contains the following fields and controls:

- Name:
- Base Type:
- Class:
- Category:
- Description:
- Life Method: Constant Life Optimal Life

Buttons on the right include "Calibration...", "Reset Defaults", "OK", and "Cancel". A status bar at the bottom reads "Vehicle type's name".

Figure 4.6 Vehicle Characteristics of Heavy Truck

Figure 4.7 depicts the attributes such as passenger car space factor, tyre type, axle configuration of respective commercial vehicles plying on this road network.

The screenshot shows the same dialog box as Figure 4.6, but with more detailed attributes visible. The "Basic Characteristics" tab is active, and the fields are organized into sections:

- Physical:**
 - Passenger Car Space Equiv:
 - No. of Wheels:
 - No. of Axles:
- Tyres:**
 - Tyre type:
 - Base no. of recaps:
 - Retread cost: %
- Utilisation:**
 - Annual km: km
 - Working hours: hrs
 - Average life: years
 - Private use: %
 - Passengers: persons
 - Work related passenger-trips: %
- Loading:**
 - ESALF:
 - Operating weight: tonnes

Buttons on the right include "Calibration...", "Reset Defaults", "OK", and "Cancel". A "Calculate..." button is present next to the Annual km, Working hours, and ESALF fields.

Figure 4.7 Vehicular Details

Figure 4.8 illustrates economic cost parameters associated with respective motorized vehicle

The screenshot shows a dialog box titled "Vehicle Attributes: heavy truck" with three tabs: "Definition", "Basic Characteristics", and "Economic Unit Costs". The "Economic Unit Costs" tab is active. It contains two main sections: "Vehicle resources" and "Time Value".

Vehicle resources:

- New vehicle: 1219275
- Replacement tyre: 11000
- Fuel: 6188 per litre
- Lubricating oil: 21.6 per litre
- Maintenance labour: 30.53 per hour
- Crew wages: 2.37 per hour
- Annual overhead: 2.6
- Annual interest: 8 %

Time Value:

- Passenger: working time: 0 per hour
- Passenger: non-working time: 0 per hour
- Cargo: 0 per hour

Buttons: Calibration..., Reset Defaults, OK, Cancel.

Footnote: All costs should be expressed in the fleet currency - Rupee

Footer: The average cost of lubricants (per litre)

Figure 4.8 Economic Cost Data related to Heavy Truck

Figure 4.9 depicts the traffic count in terms of AADT for the selected sections.

The screenshot shows a dialog box titled "Project: THESIS" with tabs: "General", "Select Sections", "Select Vehicles", and "Define Normal Traffic". The "Define Normal Traffic" tab is active. It displays a table of traffic counts for various sections.

Section	ID	Motorised AADT	NMT AADT	Year
NE-1GJ (KM 14-15)	NE- AHM-VA	8387.00	0.00	2011
NE-1GJ (KM 19-20)	NE- AHM-VA	8387.00	0.00	2011
NE-GJ (KM 15-14)	NE- AHM-VA	8304.00	0.00	2011
NH-14GJ (KM 380.6-379.6)	NH- RAD-DE	3715.00	0.00	2011
NH-2UP01	NH- ALL-VA	4789.00	0.00	2011
NE-1GJ(KM 32-31)	NE- AHM-VA	8304.00	0.00	2011
NH-37AS (KM 177.30-178.30)	NH- NAG-GL	4316.00	0.00	2011
NH-2UP02	NH- ALL-VAI	4906.00	0.00	2011
NH-4KA (KM 46-45)	NH- TM-BA	16789.00	0.00	2011
NH-4KA(481-482)	DH-BL	5088.00	0.00	2011
NH-4KA(82-83)	NH-4KA3	11456.00	0.00	2011
NH-4MH(539-538)	NH-4MH01	5029.00	0.00	2011

Buttons: Copy, Paste, Edit Section Traffic Details...

Footer: Normal Traffic for the Project

Figure 4.9 Section wise Traffic Count

4.6 PROJECT ANALYSIS

Predicting the long term pavement performance model along with corresponding economic costs for the candidate road sections in this study has been carried out on project level using this application tool. Figure 4.10 represents the general information of project analysis

The screenshot shows the 'Project: THESIS' application window with the 'General' tab selected. The interface includes a sidebar with navigation buttons: 'Define Project Details', 'Specify Alternatives', 'Analyse Projects', 'Generate Reports', 'Save', and 'Close'. The main area contains the following fields:

- Description:** PMMS for NH network
- Analyse by:** Section Project
- Start year:** 2019 **Analysis period:** 20 years
- Road Network:** NH
- Vehicle Fleet:** net
- Currencies:**
 - Fleet: Rupee × 1 = output currency
 - Works: <none> × 1 = output currency
 - Output: Rupee

Figure 4.10 General Project Details

Figure 4.11 represents the candidate road sections for which the RMMS has been developed. Based on extensive literature survey calibration factors have been adopted and assigned to this road network for analysis

The screenshot shows the 'Project: THESIS' application window with the 'Select Sections' tab selected. A checkbox labeled 'Show unselected sections' is checked. Below it is a table with columns 'Include', 'Description', and 'ID'. All rows have a checked 'Include' box. At the bottom, there are buttons for 'Select by Criteria...', 'Unselect All', 'View/Edit Section...', and 'View/Edit Network...'.

Include	Description	ID
<input checked="" type="checkbox"/>	NE-1GJ (KM 14-15)	NE-AHM-VA
<input checked="" type="checkbox"/>	NE-1GJ (KM 19-20)	NE-AHM-VA
<input checked="" type="checkbox"/>	NE-1GJ (KM 32-31)	NE-AHM-VA
<input checked="" type="checkbox"/>	NE-GJ (KM 15-14)	NE-AHM-VA
<input checked="" type="checkbox"/>	NH-14GJ (KM 380.6-379.6)	NH-RAD-DE
<input checked="" type="checkbox"/>	NH-2UP01	NH-ALL-VA
<input checked="" type="checkbox"/>	NH-2UP02	NH-ALL-VAI
<input checked="" type="checkbox"/>	NH-37AS (KM 177.30-178.30)	NH-NAG-GL
<input checked="" type="checkbox"/>	NH-4KA (KM 46-45)	NH-TM-BA
<input checked="" type="checkbox"/>	NH-4KA(481-482)	DH-BL
<input checked="" type="checkbox"/>	NH-4KA(82-83)	NH-4KA3

Figure 4.11 Sections included for Analysis

Figure 4.12 represents traffic mix (MT vehicles such as medium car, medium bus, LCV, heavy truck, articulated truck) selected for analysis

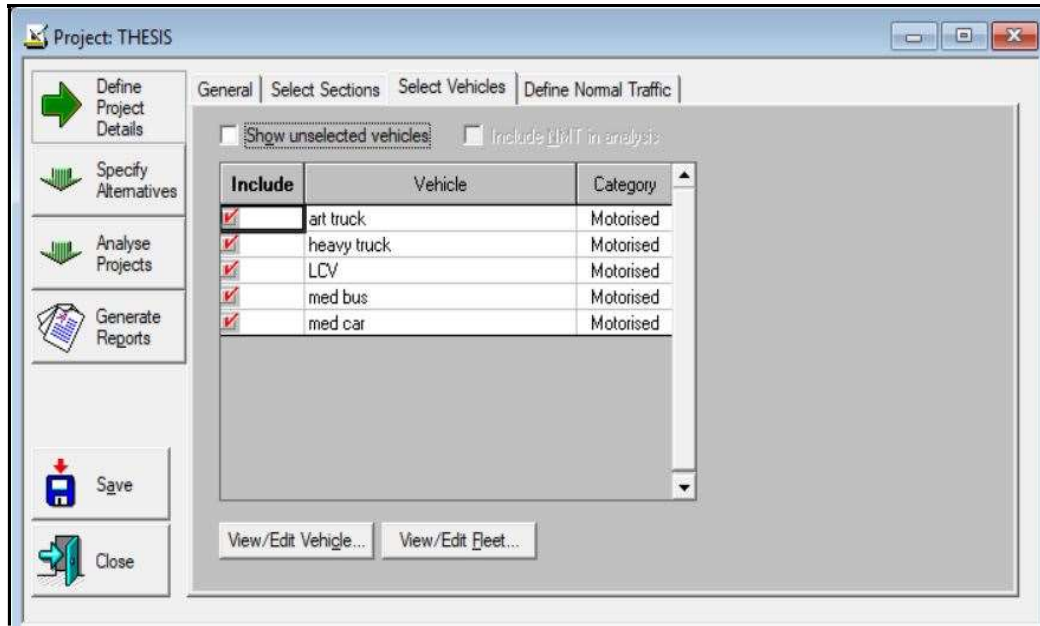


Figure 4.12 Traffic Composition for Analysis

Figure 4.13 represents the project analysis program which will generate long term pavement performance reports. These reports include pavement condition graphs, deterioration trend and economic analysis reports.

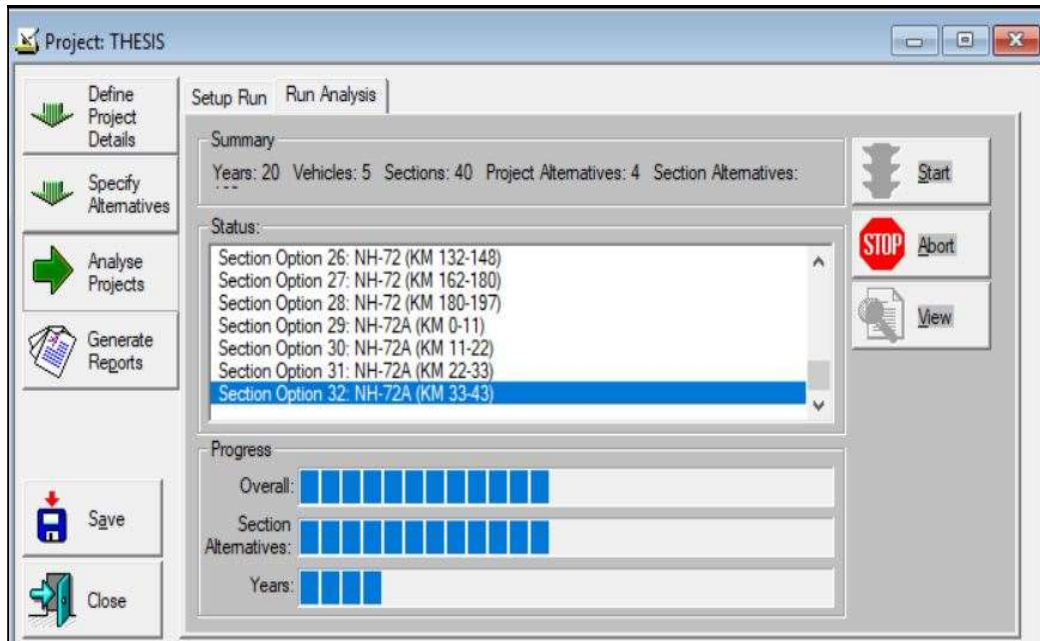


Figure 4.13 Project Analysis

4.7 RESIDUAL SERVICE LIFE OF IDENTIFIED ROAD SECTIONS

RSL is defined as the time period (in years) remaining after which reconstruction and /or rehabilitation of pavement is the only option left with the condition that no maintenance and/or rehabilitation works is carried throughout the analysis period. In this study RSL has been determined by assigning condition responsive M&R strategy for the road network. The maintenance work standards defined for this strategy is ‘Do nothing until partial reconstruction’ in which ‘Alternative 3’ which represents partial reconstruction work has been assigned. The work items include partial reconstruction of pavement crust (80 mm DBM + 40 mm BC) and the criteria for the intervention of this M&R strategy for each road section is Total damaged area > 20% and Roughness > 6mm/km. RSL has been determined using project analysis program which incorporates entire NH network and vehicle data. After specifying the M&R strategies project analysis has been performed and the corresponding results have been obtained and analysed. The trend of roughness progression has been analysed in the graphs for each road section for the analysis period (i.e. from 2019-2038). As time progresses, due to ageing of pavement the roughness value increases and at certain point within the graph there is sudden descend which indicates reconstruction work is required corresponding to that year. Figure 4.14 to Figure 4.43 depicts average roughness graphs for each selected road sections:

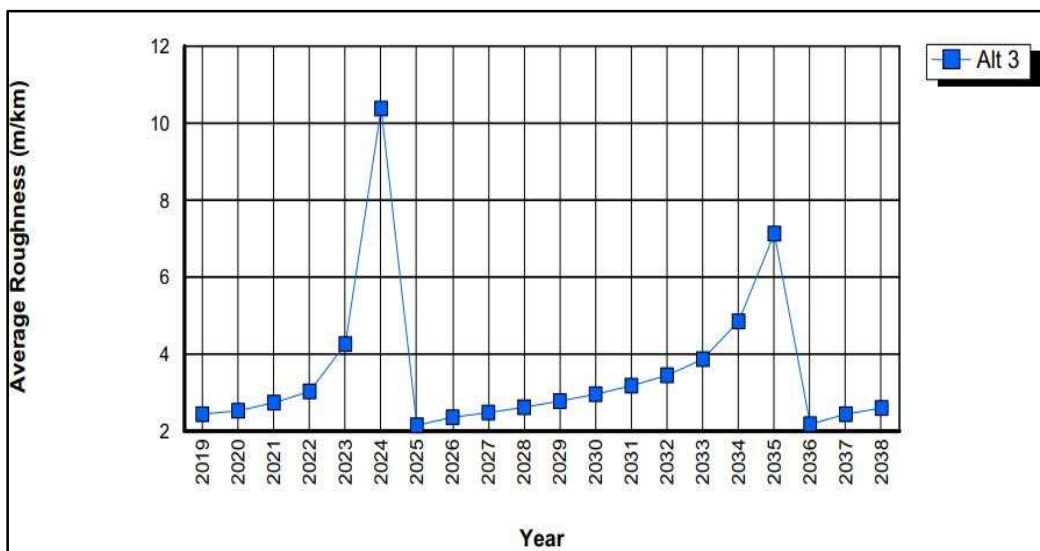


Figure 4.14 Roughness Progression graph NE-1 GJ01 (KM 14-15)

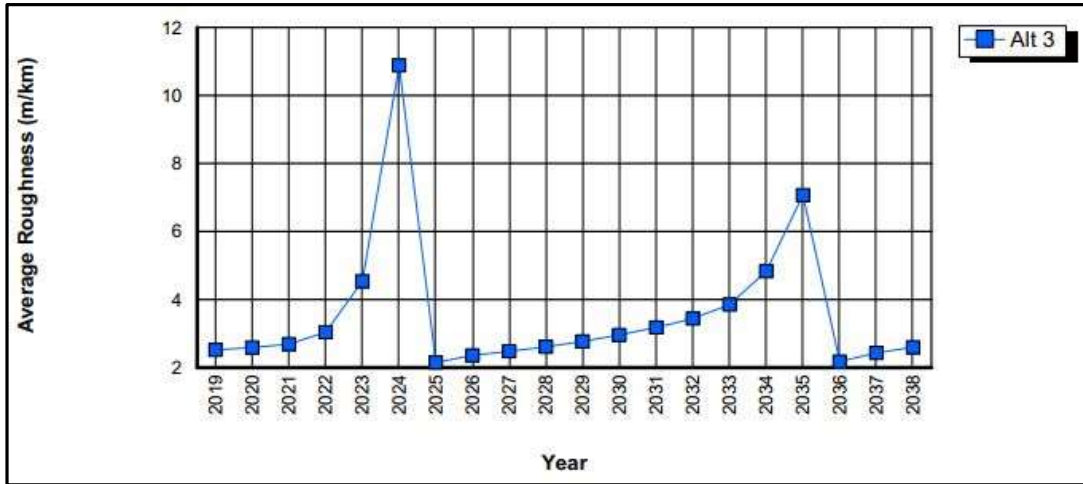


Figure 4.15 Roughness Progression graph NE-1 GJ02 (KM 19-20)

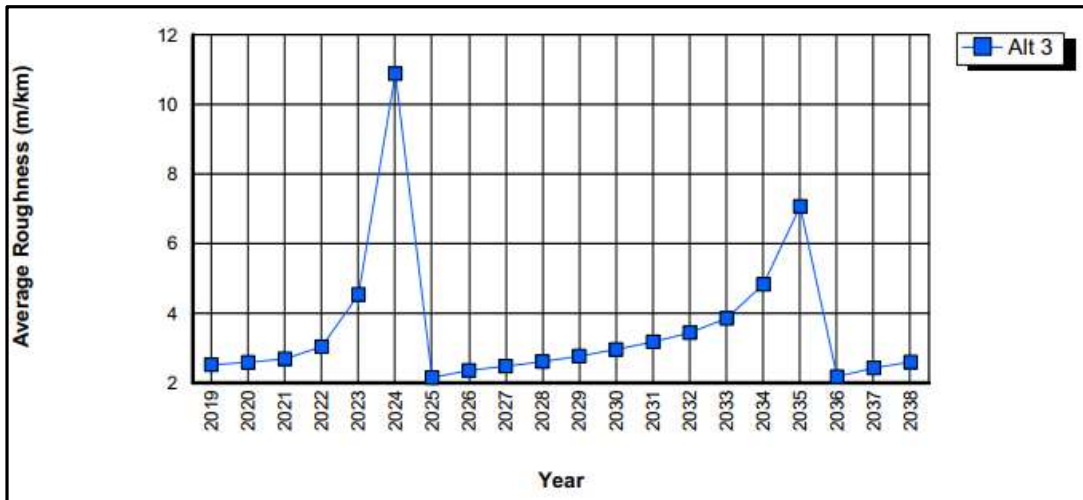


Figure 4.16 Roughness Progression graph NE-1 GJ03 (KM 32-31)

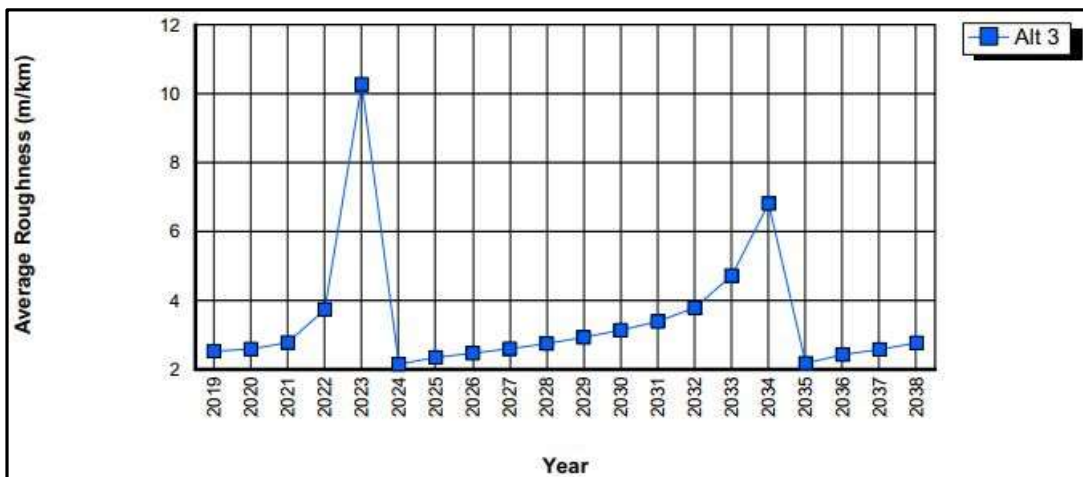


Figure 4.17 Roughness Progression graph NE-1 GJ04 (KM 15-14)

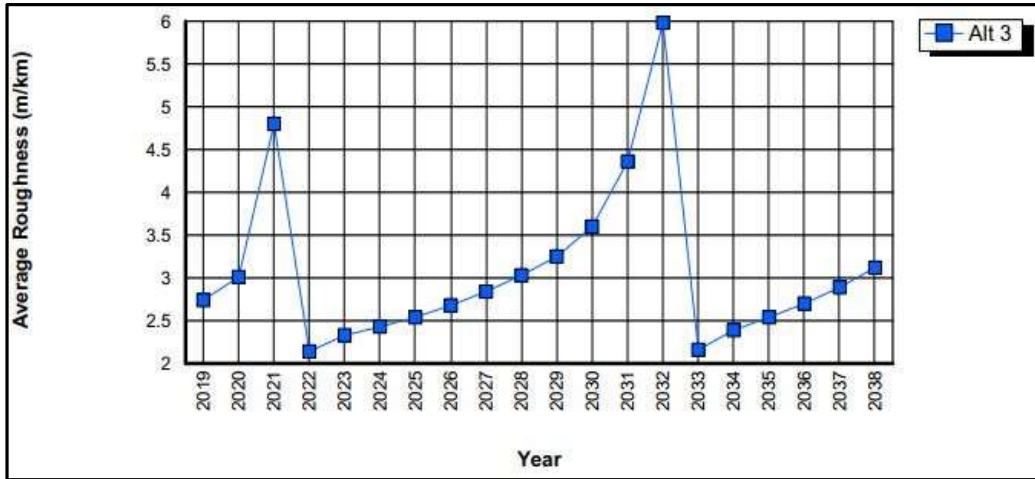


Figure 4.18 Roughness Progression graph NE-14 GJ05 (KM 380.6-379.6)

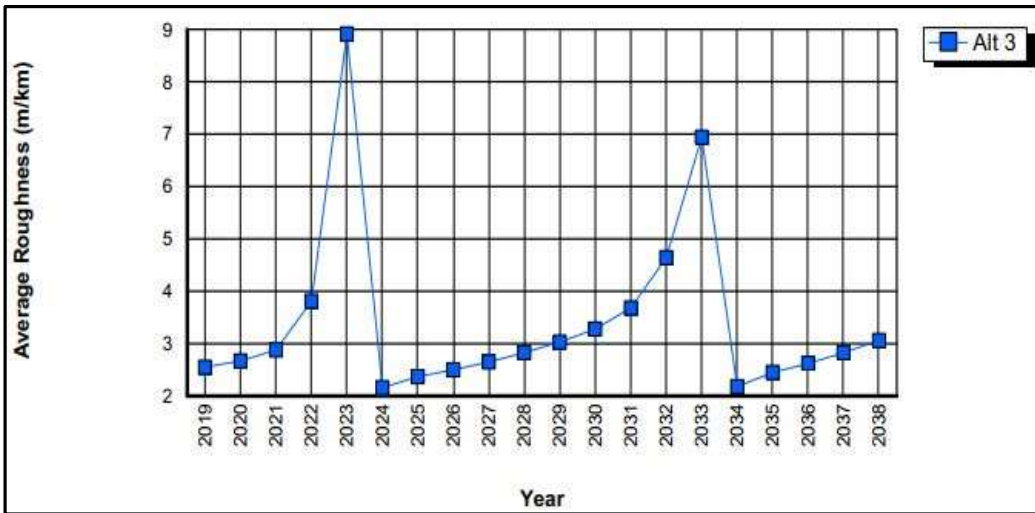


Figure 4.19 Roughness Progression graph NH-2 UP01

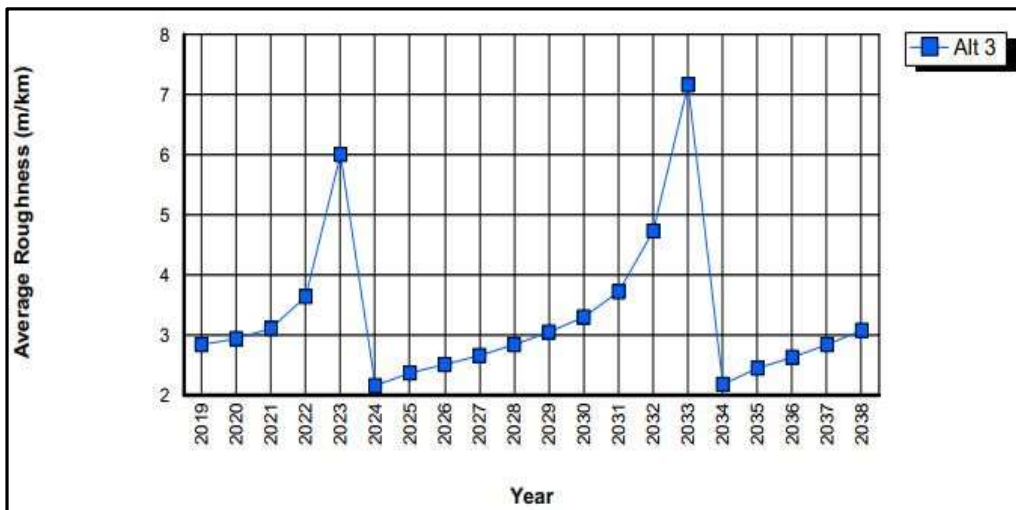


Figure 4.20 Roughness Progression graph NH-2 UP02

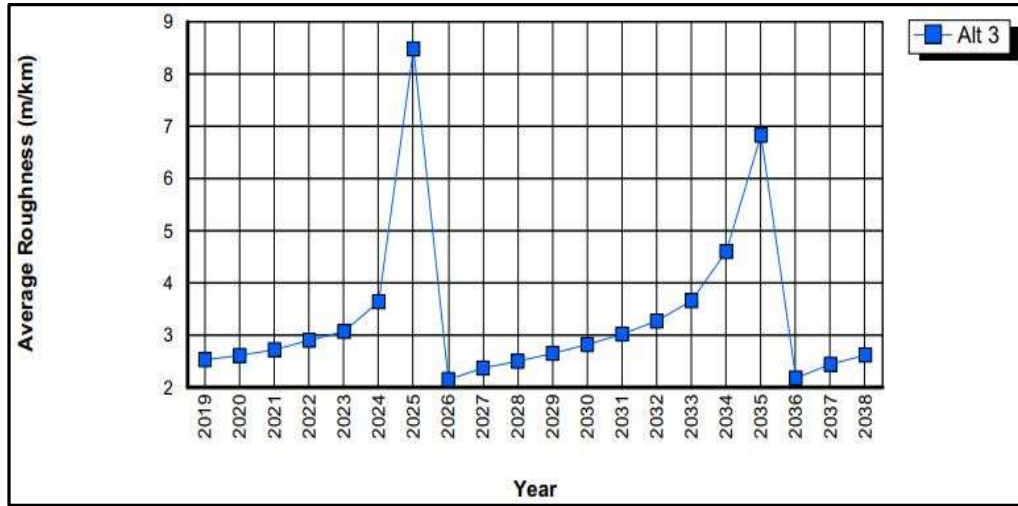


Figure 4.21 Roughness Progression graph NH-37AS (KM 177.30-178.30)

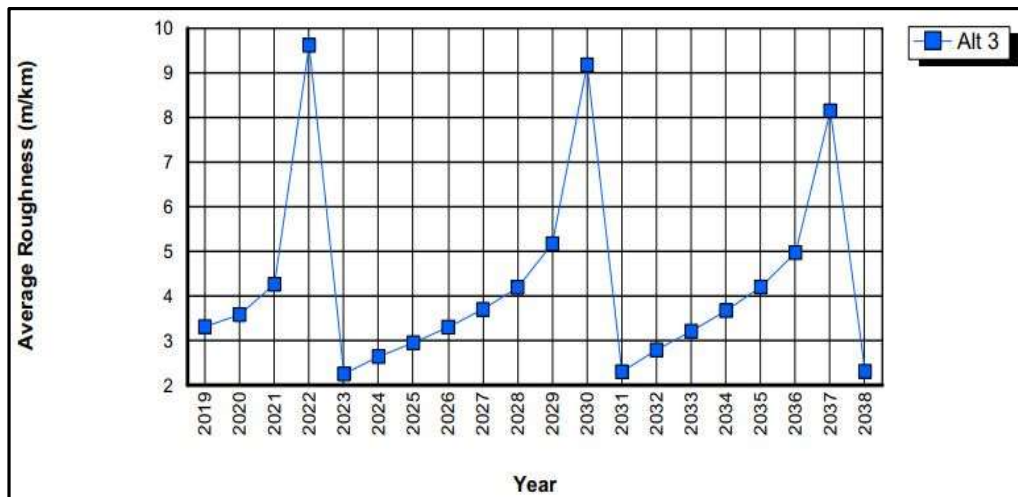


Figure 4.22 Roughness Progression graph NH-4 KA01 (KM 46-45)

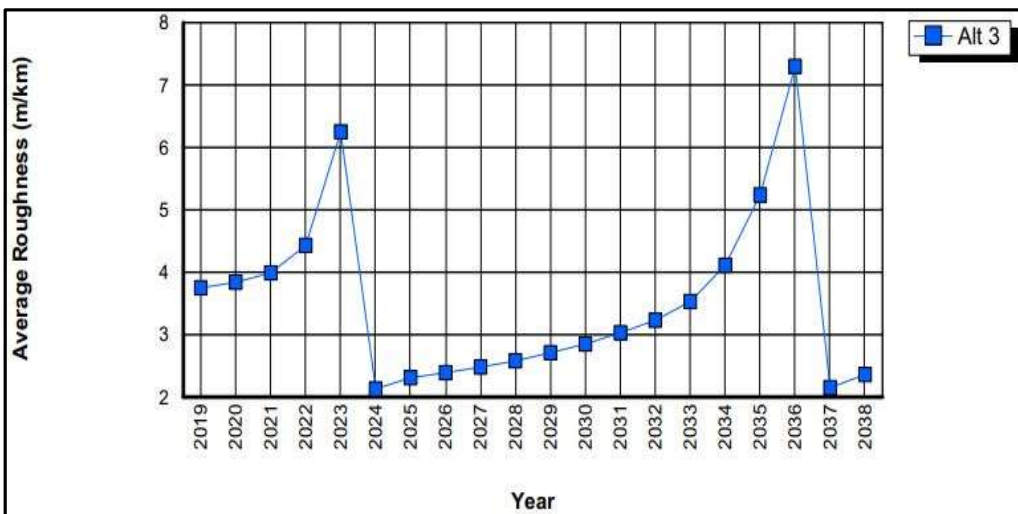


Figure 4.23 Roughness Progression graph NH-4 KA02 (KM 481-482)

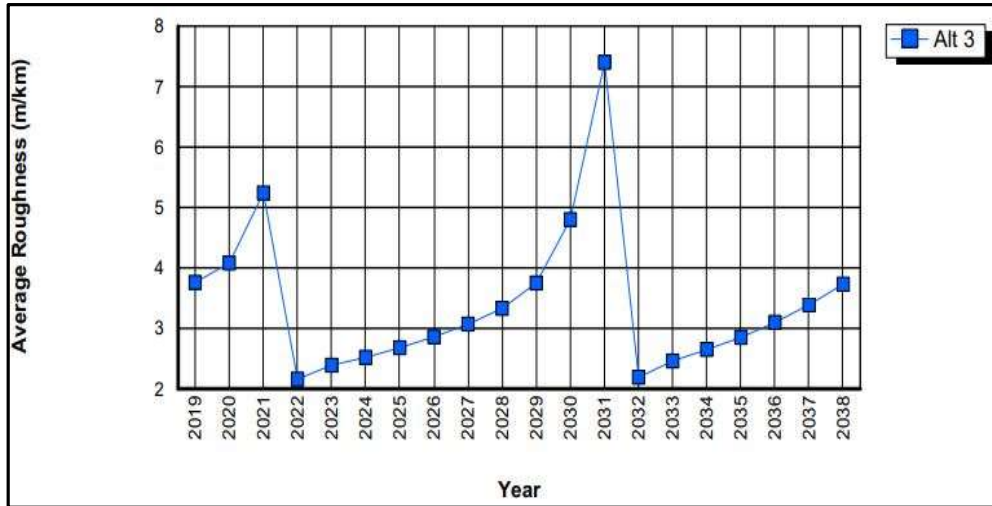


Figure 4.24 Roughness Progression graph NH-4 KA03 (KM 82-83)

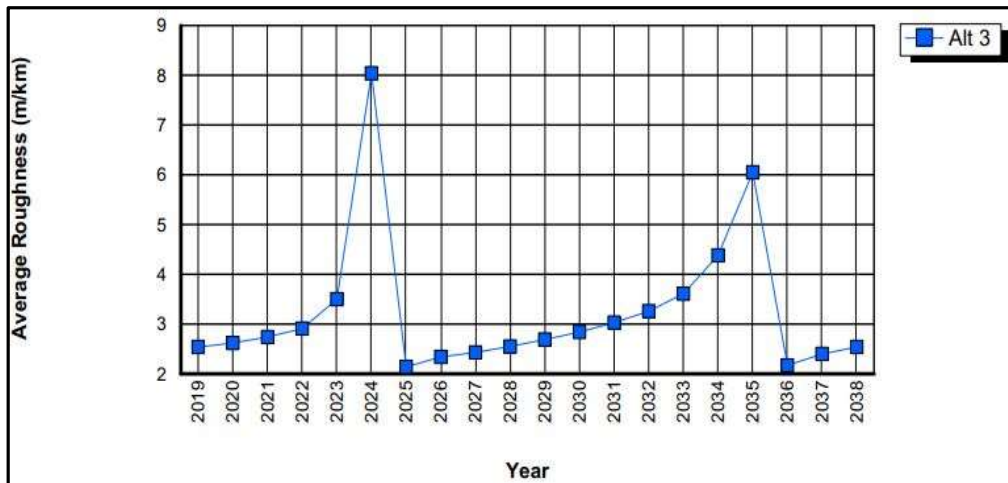


Figure 4.25 Roughness Progression graph NH-5 AP01 (KM 691.25-690.75)

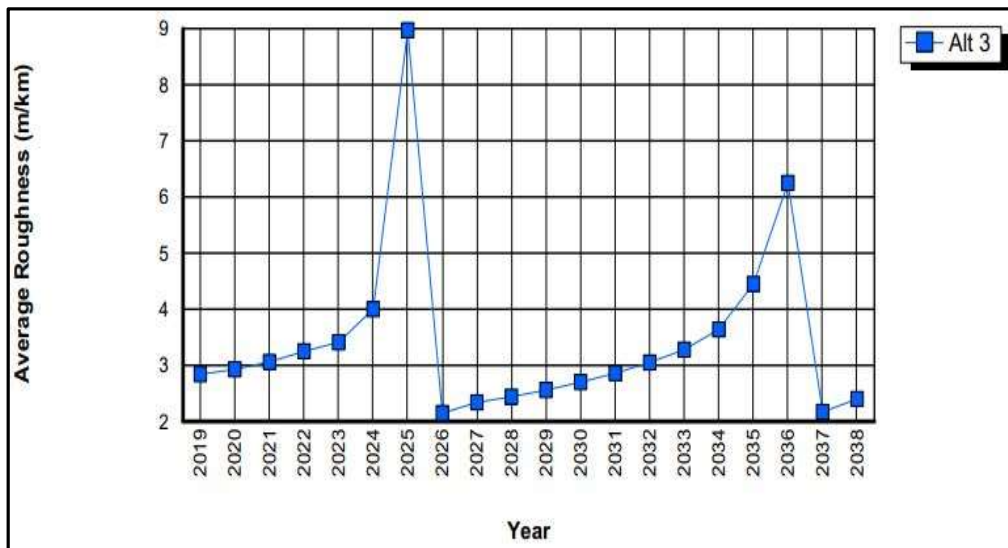


Figure 4.26 Roughness Progression graph NH-5 AP02 (KM 698.6-698.1)

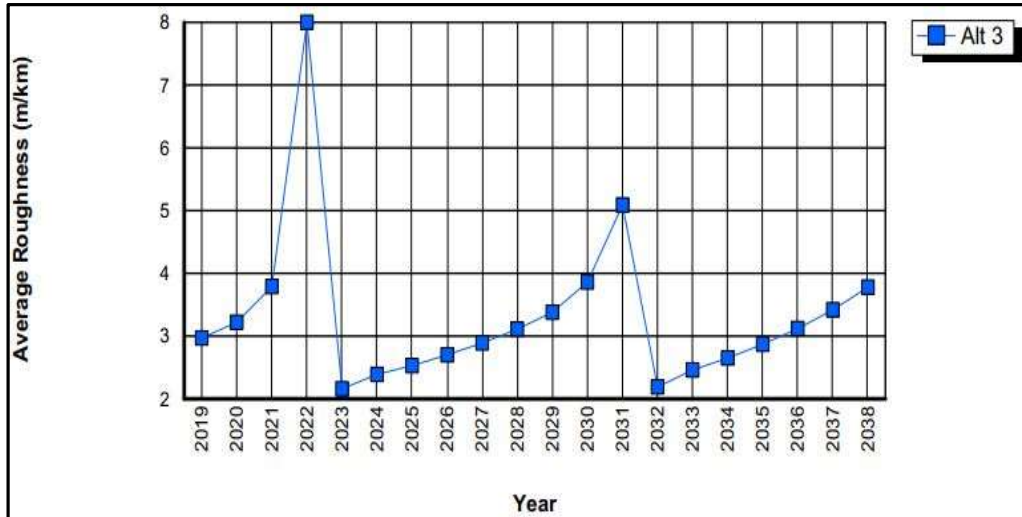


Figure 4.27 Roughness Progression graph NH-5 AP03 (KM 7.5-7)

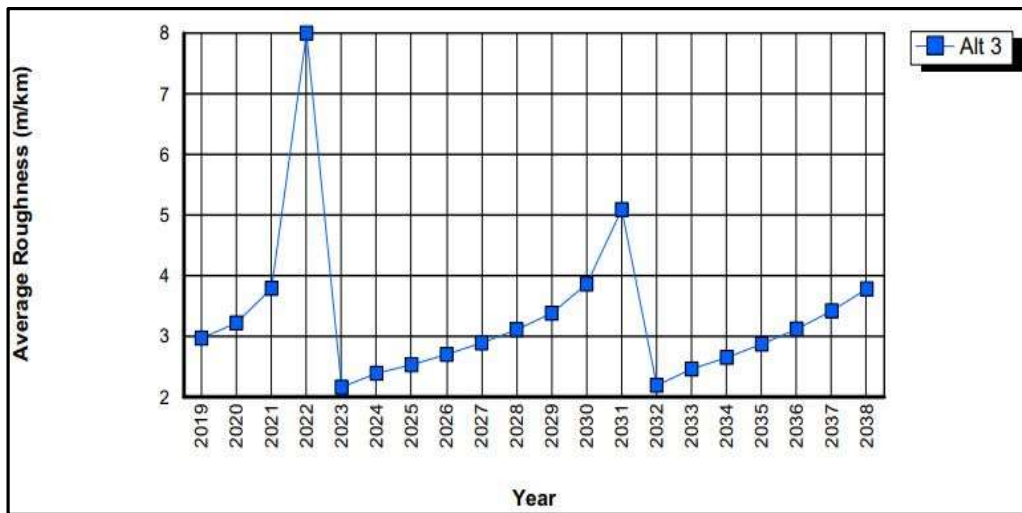


Figure 4.28 Roughness Progression graph NH-5 AP04 (KM 9.8-9.3)

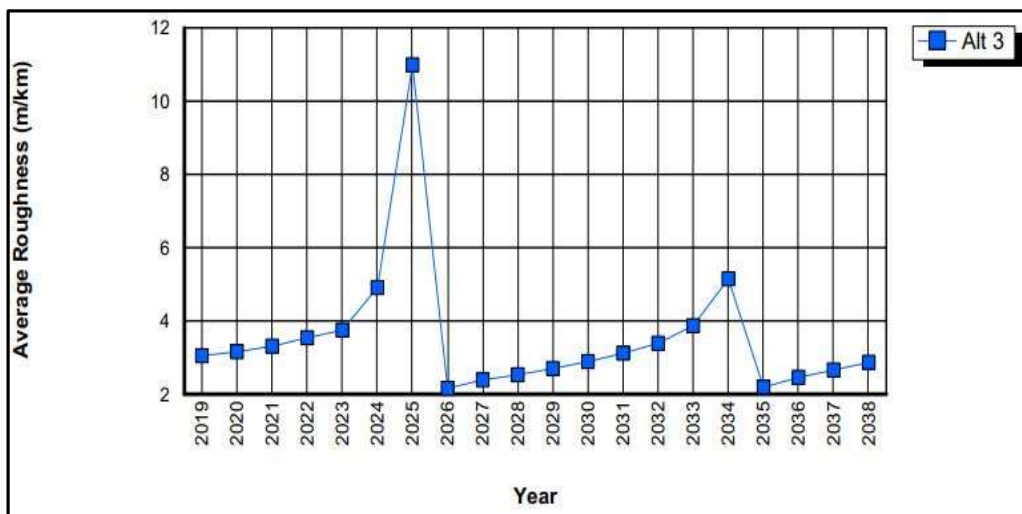


Figure 4.29 Roughness Progression graph NH-4 MH01 (KM 539-538)

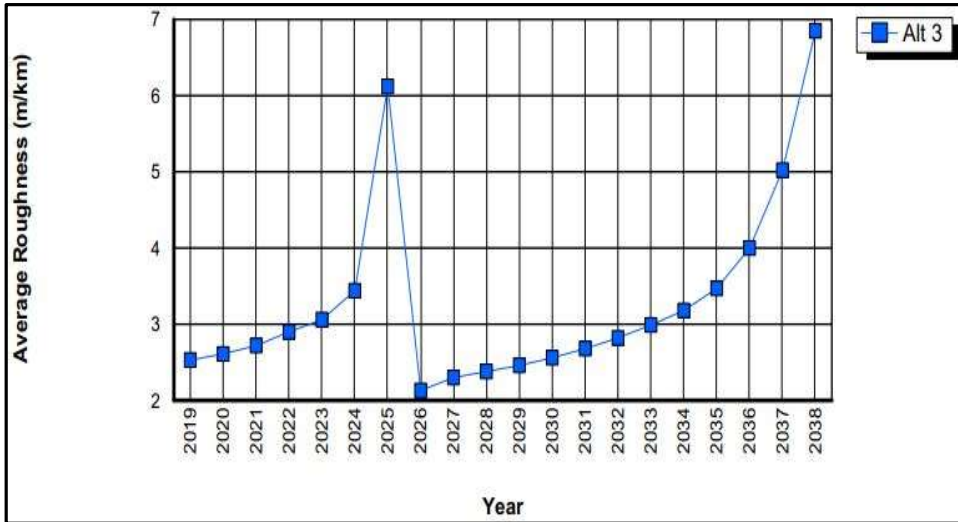


Figure 4.30 Roughness Progression graph NH-7 MH02 (KM 84.2-84.7)

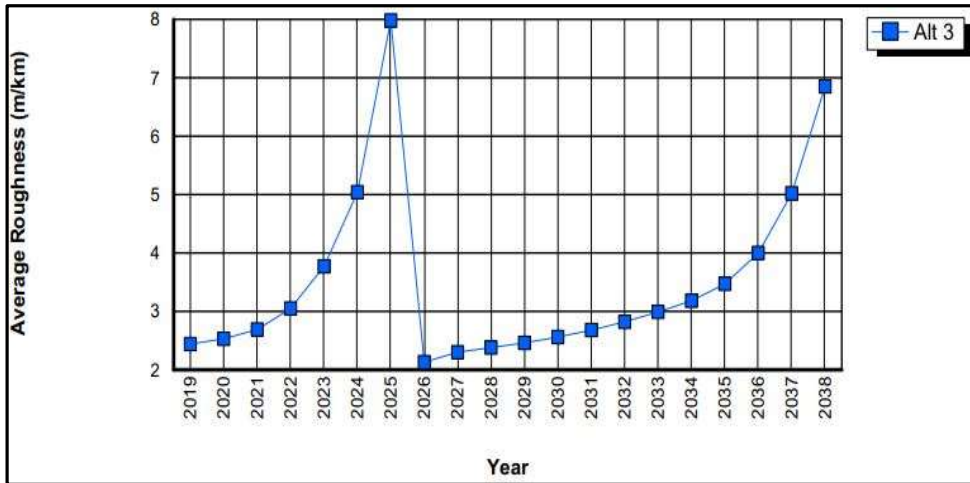


Figure 4.31 Roughness Progression graph NH-7 MH03 (KM 95.5-96)

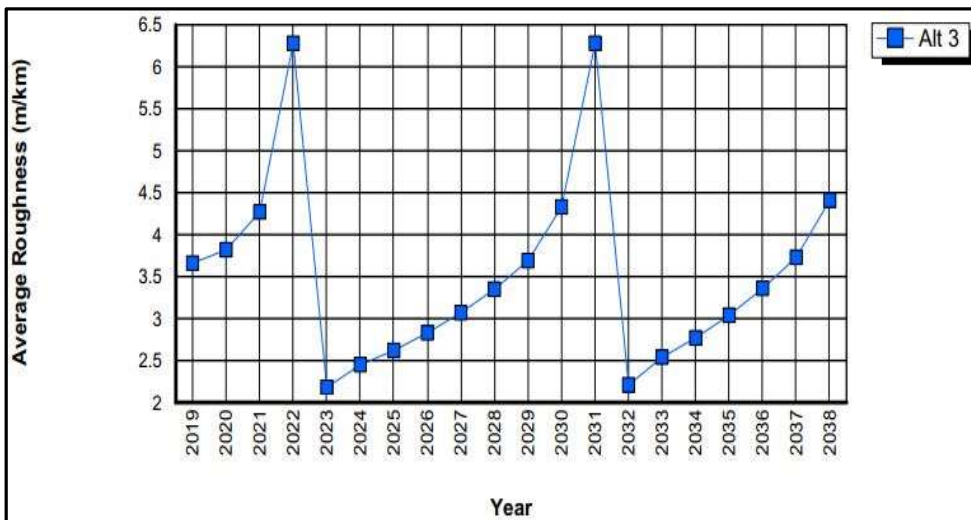


Figure 4.32 Roughness Progression graph NH-73 (KM 0-11)

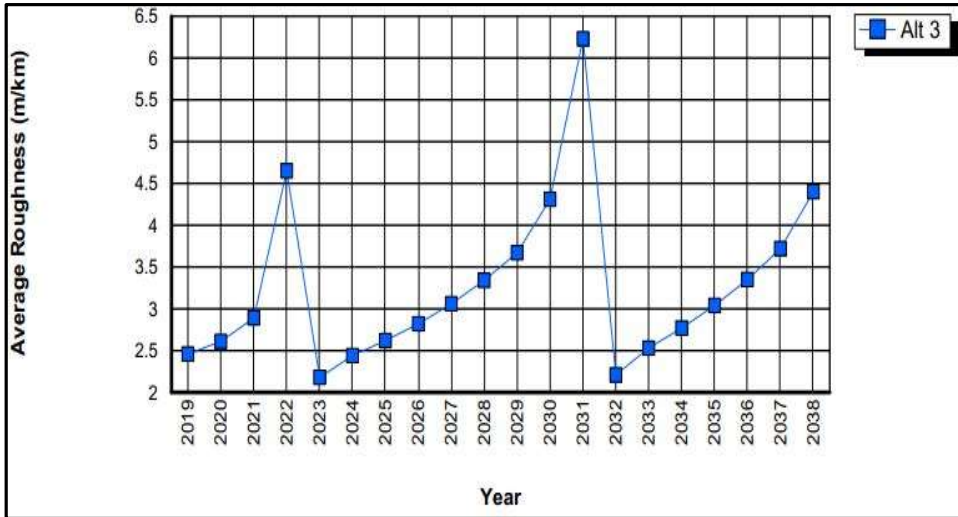


Figure 4.33 Roughness Progression graph NH-73 02 (KM 11-25)

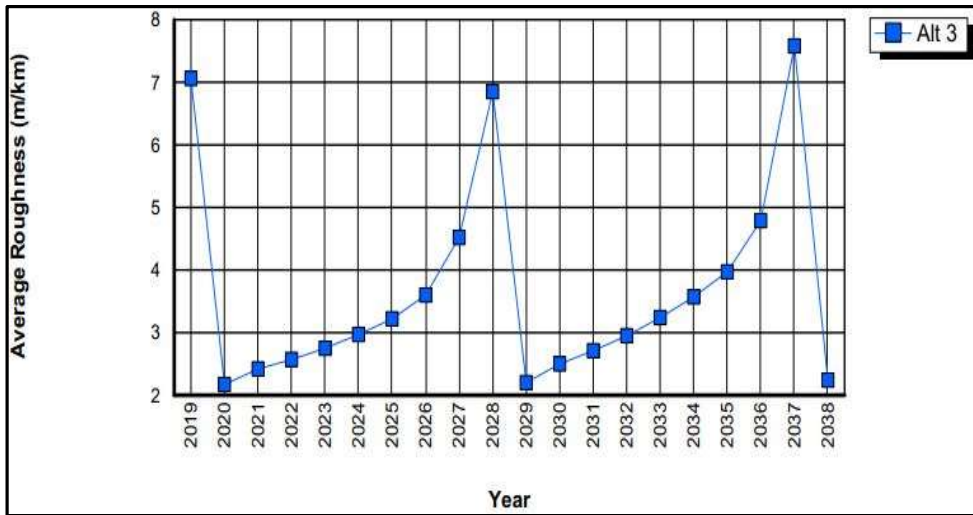


Figure 4.34 Roughness Progression graph NH-73 03 (KM 25-35)

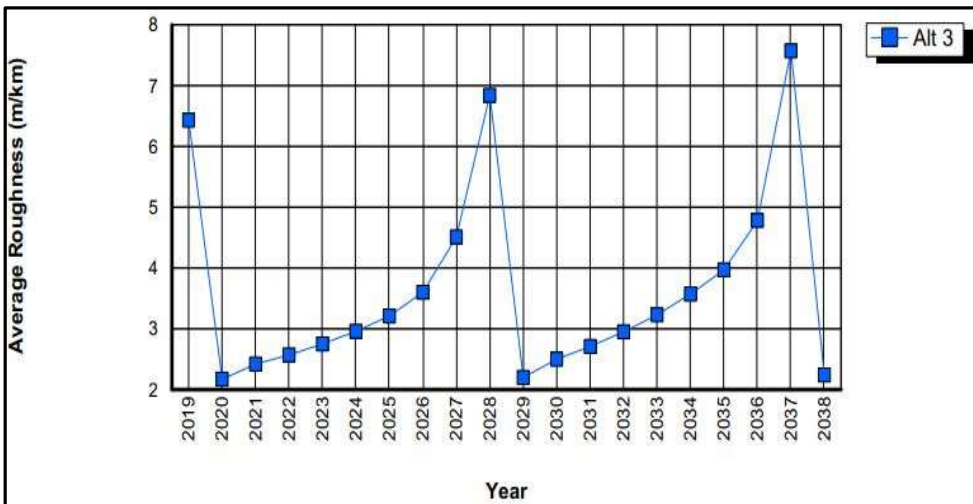


Figure 4.35 Roughness Progression graph NH-73 04 (KM 35-47)

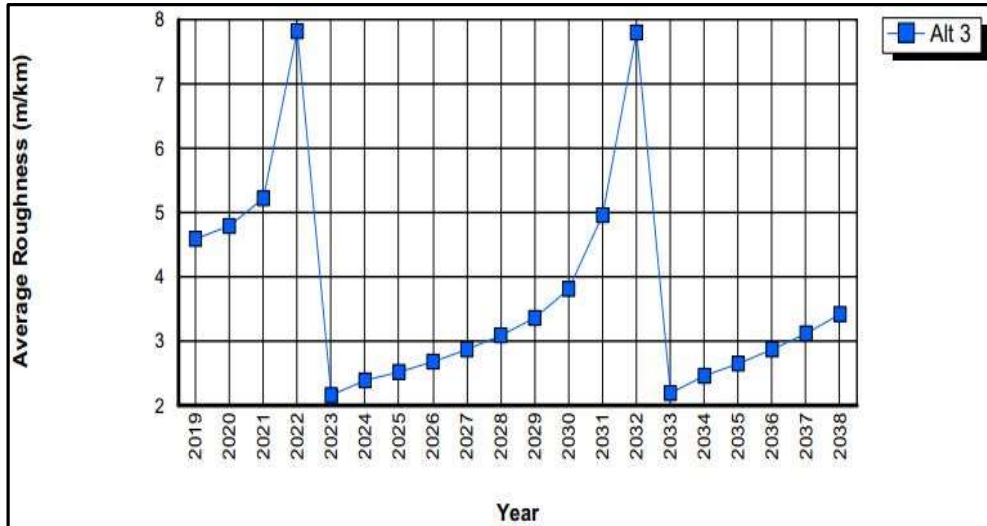


Figure 4.36 Roughness Progression graph NH-74 (KM 0-13)

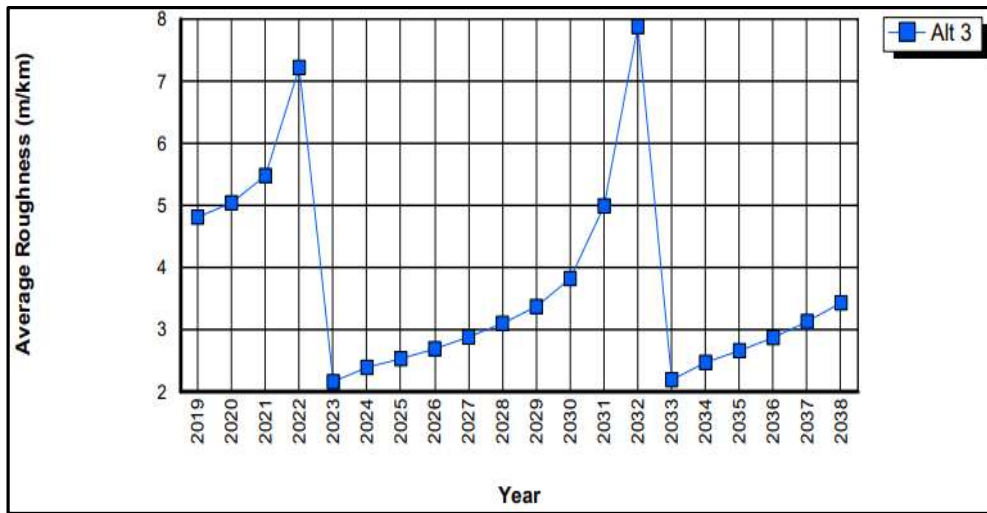


Figure 4.37 Roughness Progression graph NH-74 02 (KM 13-30)

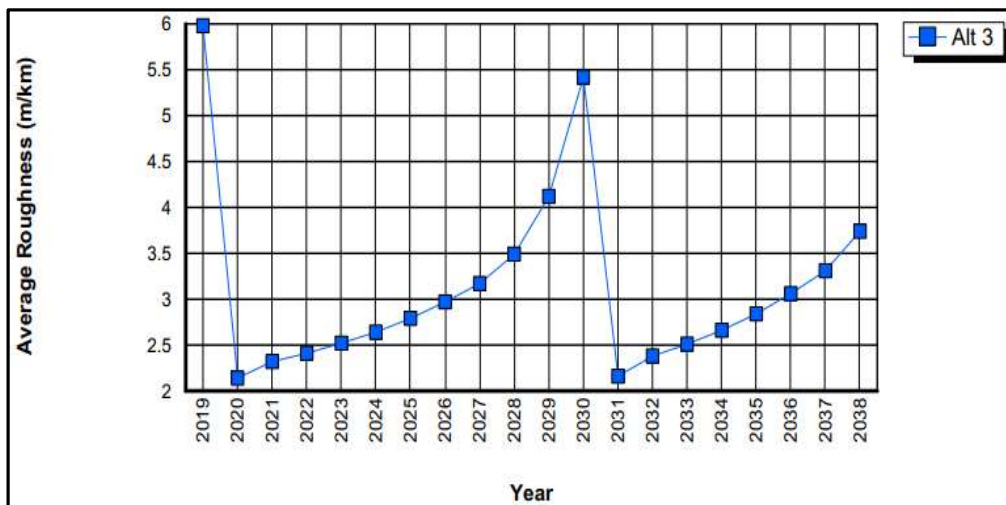


Figure 4.38 Roughness Progression graph NH-72 01 (KM 105-118)

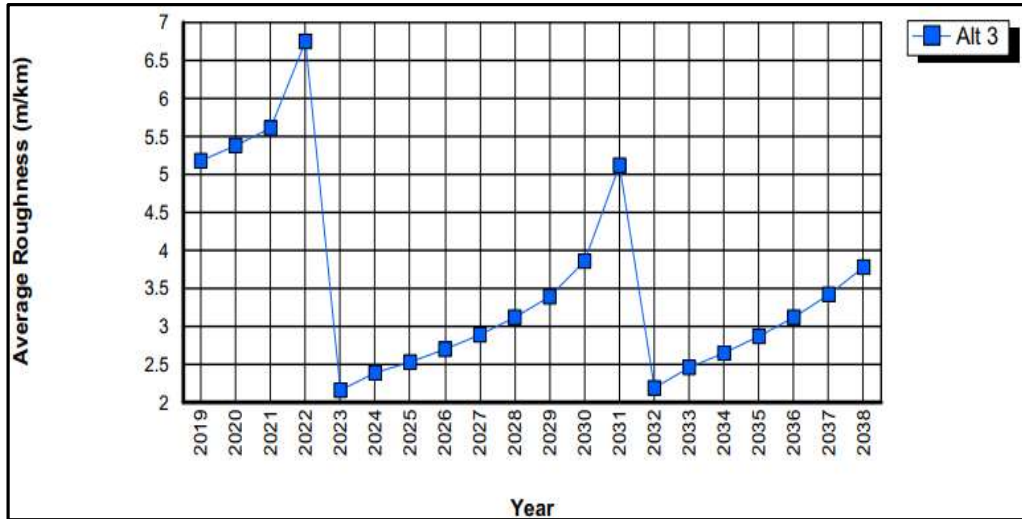


Figure 4.39 Roughness Progression graph NH-72 02 (KM 118-132)

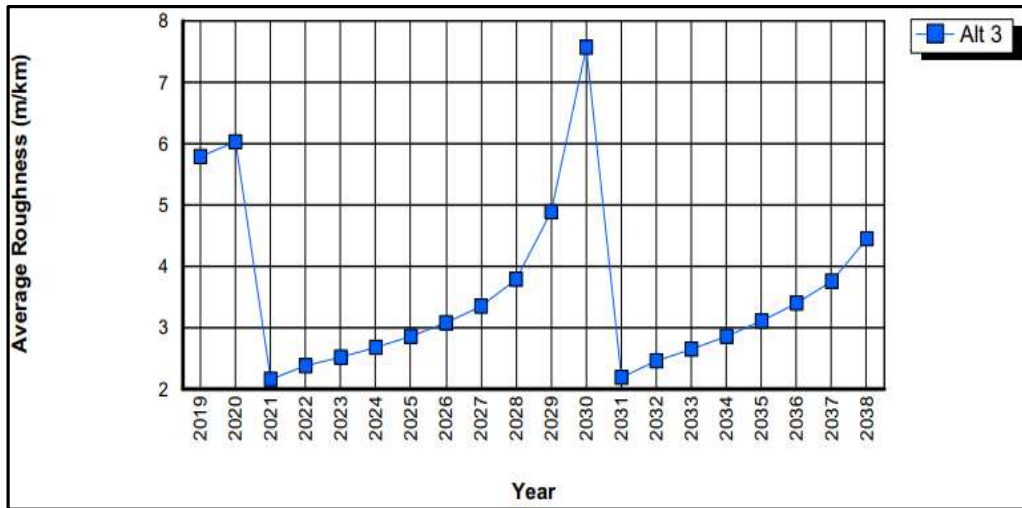


Figure 4.40 Roughness Progression graph NH-72 03 (KM 132-148)

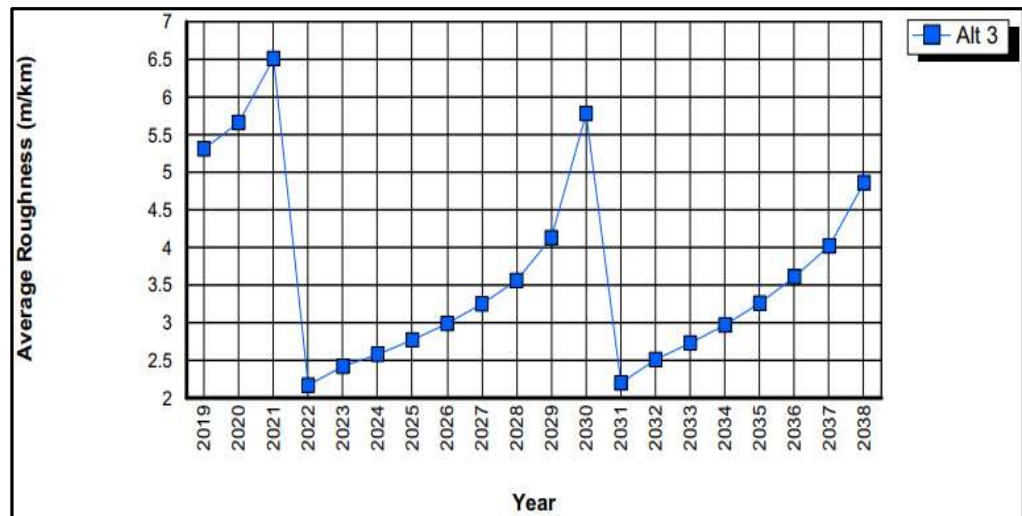


Figure 4.41 Roughness Progression graph NH-72 04 (KM 162-180)

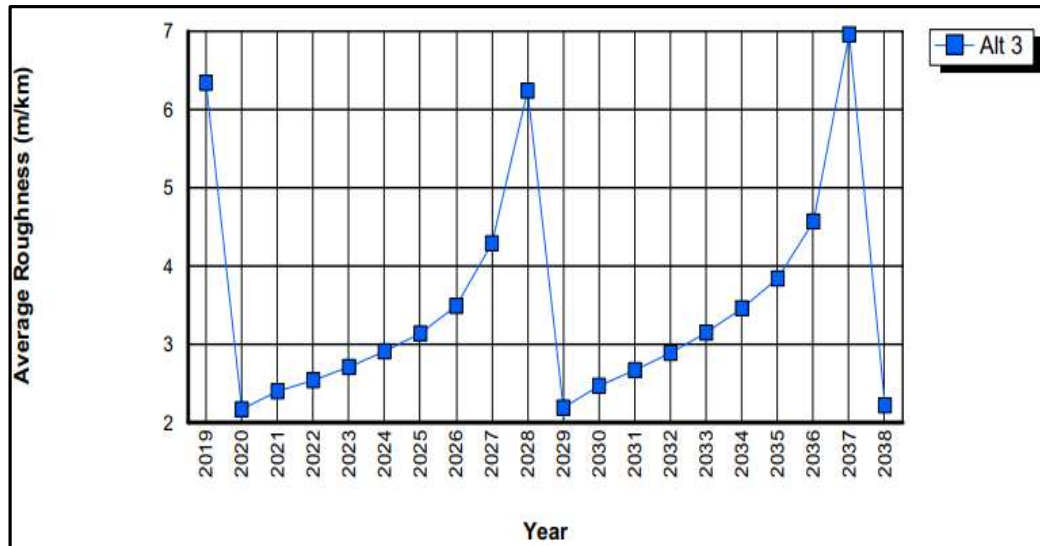


Figure 4.42 Roughness Progression graph NH-72 05 (KM 180-197)

Comments: Residual life of candidate road sections w.r.t the year when any rehabilitation and/or resurfacing work was done: for NH-73 03, NH-72 (km 115-118, 180-197), NH-73 (km 25-47) road section is 10 years, for NH-14GJ 05, NH-72 (km 132-148) road section is 11 years, for NH-4KA 01, NH-4KA 03, NH-5AP 03, NH-5AP 04, NH-74, NH-73 01, NH-73 02 road sections is 12 years, for NE-1GJ 04, NH-2UP 01, NH-2UP 02, NH-72 (km 118-132), NH-72A (km 0-25), NH-74 (km 0-30) road sections is 13 years, for NE-12UP, for NE-1GJ 01, NE-1GJ 02, NE-1GJ 03, NH-4KA 02, NH-5AP 01 road sections is 14 years, for NH-4MH, NH-5AP 02, NH-7MH 03, NH-7MH 02 road sections is 15 years. Pavement service life is a function of various parameters such as pavement strength, projected traffic, road geometrics, construction quality, subgrade compaction, climatic conditions and most importantly the maintenance strategies adopted in the previous years. Therefore, it can be observed from the roughness graphs plotted above that the RSL varies for different road sections.

4.8 WORK STANDARDS MODEL MANAGER

Work standards input model in HDM provides the road agencies with variety of maintenance options which can be selected and analysed throughout the pavement life cycle. M&R strategies includes various work activities that can be assigned to sections within the road network. The type and criteria of work intervention will be governed by pavement condition, traffic loading, pavement history and economic factors. Table 4.4 represents various maintenance and treatment works prescribed under different classes of road works.

Table 4.4 Categorization of Road Works

Works category	Works Class	Works Type	Works Activity/Operation
Preservation		Routine Pavement	patching, edge repair, crack sealing, spot-regravelling, shoulder repair etc.
		Drainage	culvert repairs, clearing side drains etc.
	Routine Maintenance	Routine Miscellaneous	vegetation control, signs, line markings etc.
		Preventive Treatment	fog seal, rejuvenation etc.
		Resurfacing	surface dressing, slurry seal, cape seal, regravelling etc.
	Periodic Maintenance	Rehabilitation	thick overlay, mill and replace, inlay
		Reconstruction	partial reconstruction (Major Overlay), full pavement reconstruction
	Special Repairs	Emergency	clearing debris, repairing washouts/subsidence etc.
		Widening	partial widening, lane addition
	Realignment	horizontal and vertical geometric improvements	
Development	Improvement	Off-carriageway	shoulders addition, shoulders upgrading, NMT lane addition
		Upgrading	changing the road surface class
	Construction	New section	widening of existing section, new section (link)

Source: Odoki and Kerali (2000)

4.8.1 Maintenance Work Types

The type of maintenance works to be assigned to particular road section at specific point of time mainly depends upon the target level of serviceability. Each work type corresponds to different set of work operations or activities that can be applied based on pavement classification. Following are the maintenance work types:

- **Routine maintenance** – This type of works overcome minor pavement defects such as cracking and potholes that are induced due to combined effect of traffic loading and environmental effects. Routine maintenance works have to be

scheduled each year or at fixed intervals within a year. For bituminous pavements, work activities such as crack sealing and patching fall under this work type.

- **Periodic maintenance** – These are work activities that have to be undertaken at intervals of several years. Resealing, surface treatments, overlays, inlays, mill, replace and reconstruction are periodic maintenance works preferred on bituminous roads.

4.8.2 Intervention Criteria

Planning and scheduling of various maintenance works comes with certain intervention levels set by the road agencies based on physical characteristics of road network. Intervention criteria includes limits and timing of selected maintenance works. The intervention type will reflect on the road agency cost and road user cost in terms of reduction in one or more pavement distress parameters. Scheduled type and condition responsive are the two types of M&R strategies.

- **Scheduled type** – Work activities scheduled at fixed intervals of time (for example, resealing and patch work after every four years)
- **Condition responsive type** – Work activities assigned only when the specified intervention criteria such as pavement strength, distresses, traffic reaches its critical limit.

4.8.3 Proposed Work Alternatives

In this study four work alternatives have been assigned to all the road sections of NH network. Each work alternative has specific work activities/operations and intervention limits. A scheduled type M&R strategy which is the base alternative has been considered which includes work items viz. crack sealing and patching. The remaining three work alternatives are condition responsive type which comprises of partial reconstruction (major overlay), resealing & overlay, resealing work activities. Work operations under the scheduled type M&R strategy have been assigned as per the typical maintenance standards prescribed by road administration (MORT&H 2001). On the other hand, the condition responsive strategy has been proposed in accordance with the target serviceability levels. Table 4.5 represents maintenance work program assigned to entire road network for life cycle analysis of project.

Table 4.5 Proposed Work Strategies

M&R Strategy	Work Standard	Work Description	Intervention Limits
Base Alternative	Routine Maintenance	Crack sealing + Patching	Scheduled Annually
Alternative 1	Resealing	Provide 25 mm DBSD	Total damage area > 5% of total area
Alternative 2	Resealing + Thin Overlay	Provide 25 mm DBSD and 25 mm BC	Total damage area > 5% of total area and Roughness IRI > 3 m/km
Alternative 3	Major Overlay (Partial Reconstruction)	Provide 80 mm DBM (binder course) + 40 mm BC (wearing course)	Roughness (IRI) > 6 m/km and total damage area > 20%

Figure 4.44 depicts all the M&R alternatives considered and assigned to each road section for performing project analysis.

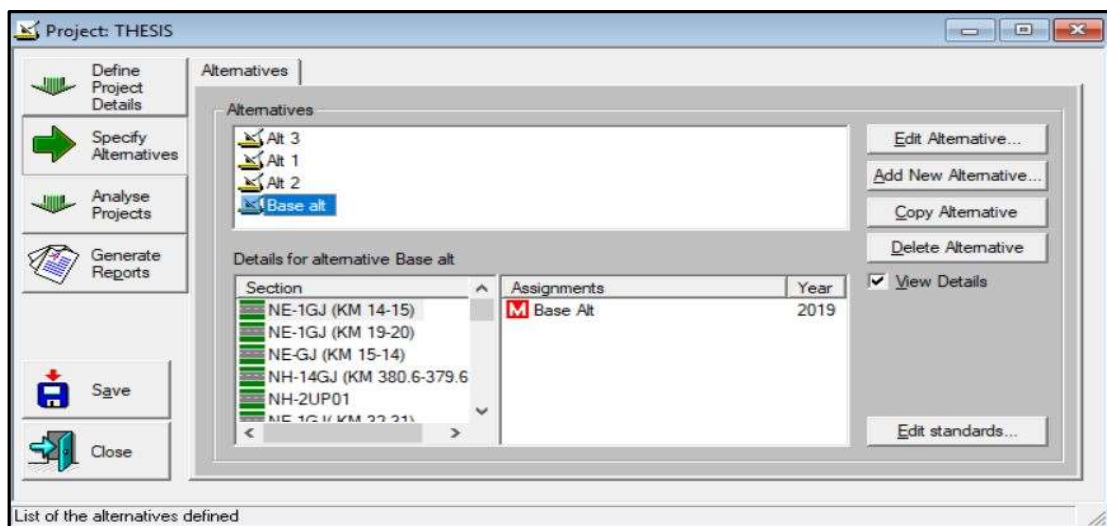


Figure 4.43 Alternatives Defined for Project Analysis

Figure 4.45 represents “Base Alternative” which is classified as Routine Maintenance work and includes crack sealing and patching as its work items. The intervention type proposed for both the work items are scheduled type and have been fixed after an interval of one year.

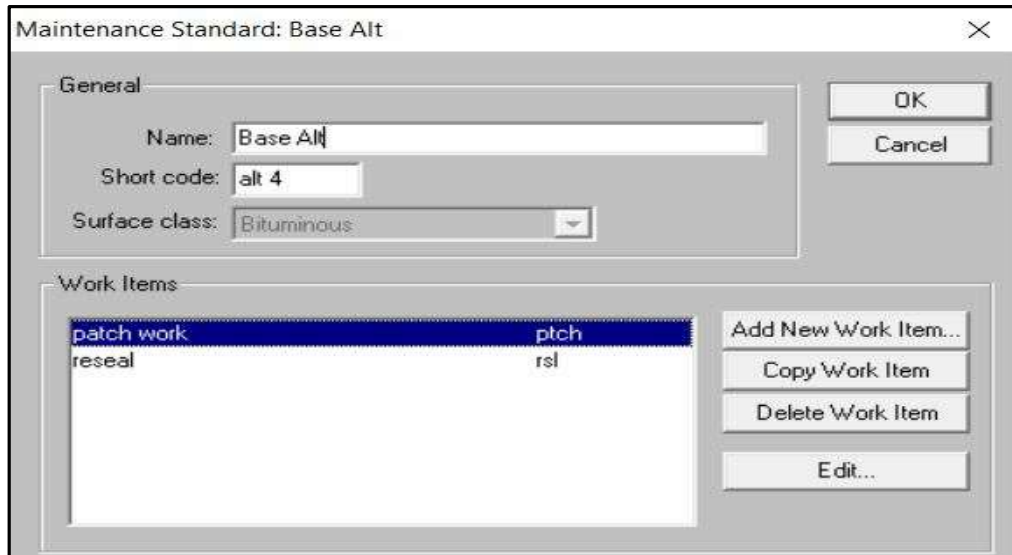


Figure 4.44 Base Alternative (Routine Maintenance)

Figure 4.46 shows “Alternative 2” maintenance work strategy which will intervene when critical limits i.e. total damaged area $\geq 5\%$ of paved area and roughness value ≥ 3 m/km are reached. Work items include resurfacing with DBSD (25 mm) + Asphaltic concrete (40 mm).

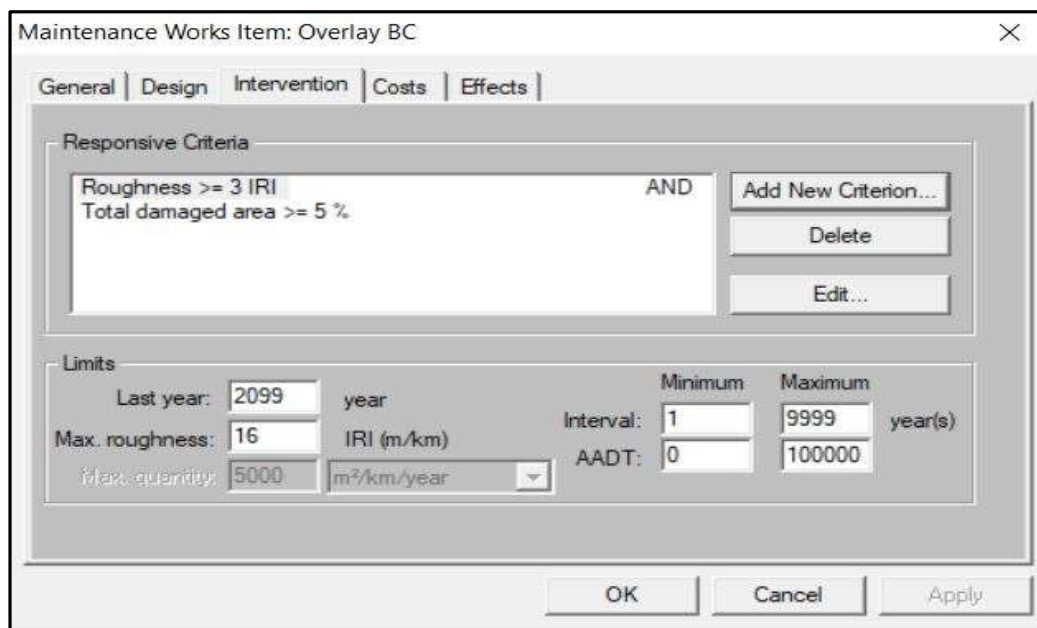


Figure 4. 45 Intervention Limits for Alternative 2

“Major Overlay” work has been assigned to “Alternative 3” M&R strategy which will respond when intervention limits i.e. Roughness ≥ 6 m/km and total damage area $\geq 20\%$ are reached. Figure 4.47 shows the intervention criteria for major overlay work which is condition responsive strategy.

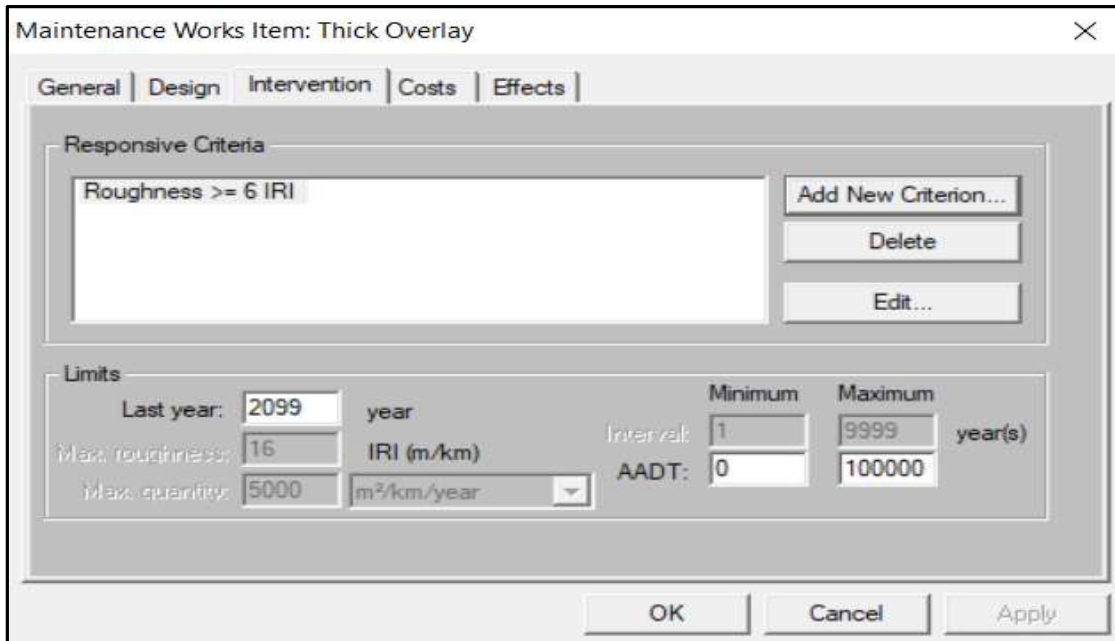


Figure 4. 46 Intervention Limits for Alternative 3

4.9 LONG TERM PAVEMENT PERFORMANCE ANALYSIS USING HDM-4 MODEL

Roughness is a reliable and powerful index to assess average pavement condition of road section at any instant. After assigning the M&R strategies for the candidate road sections, project analysis application has been run to analyse the effect of these maintenance works on long term pavement performance in terms of variation in average roughness with time.

Roughness progression graphs for each section has been obtained and the work effects have been analysed. These graphs serve as a tracker of work items and verify the intervention criteria at trigger points.

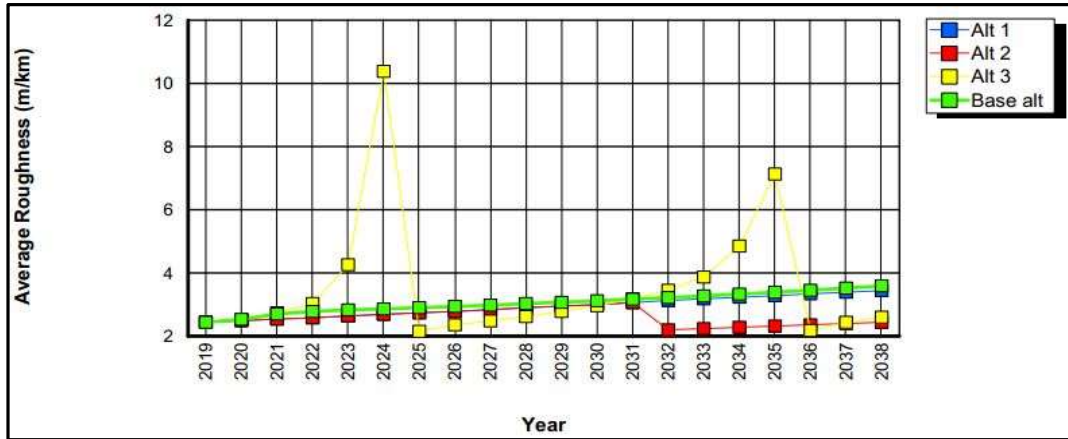


Figure 4.47 Average Roughness Trend of NE-1 GJ01 (KM 14-15) for Maintenance Standards

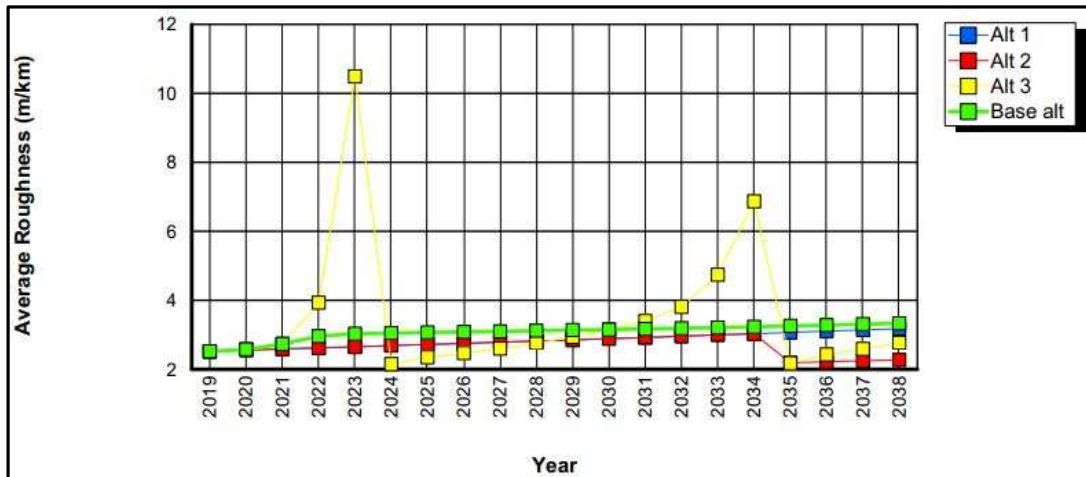


Figure 4.48 Average Roughness Trend of NE-1 GJ02 (KM 19-20) for Maintenance Standards

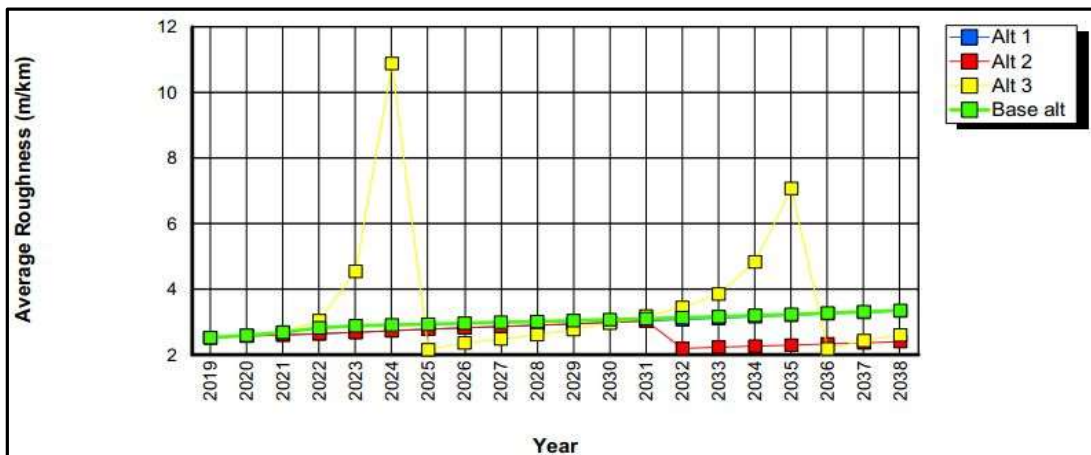


Figure 4.49 Average Roughness Trend of NE-1 GJ03 (KM 32-31) for Maintenance Standard

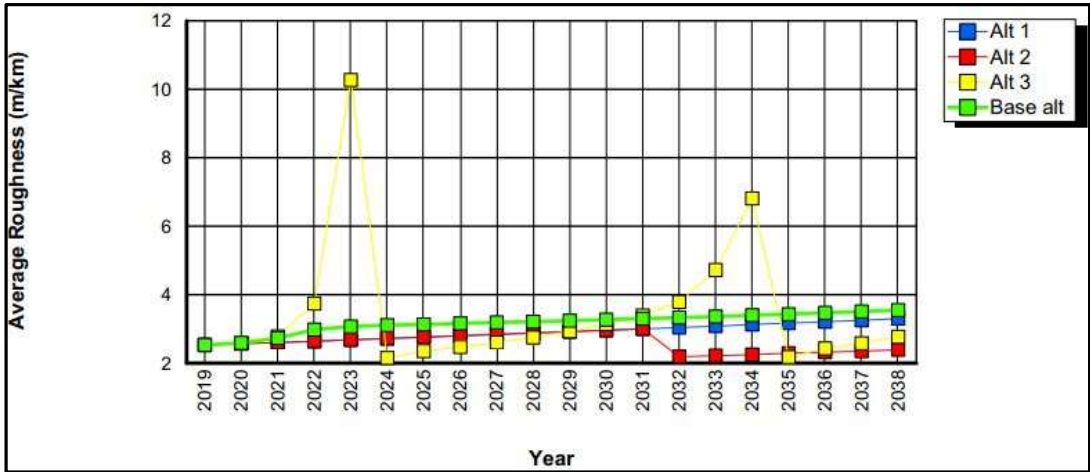


Figure 4.50 Average Roughness Trend of NE-1 GJ04 (KM 15-14) for Maintenance Standards

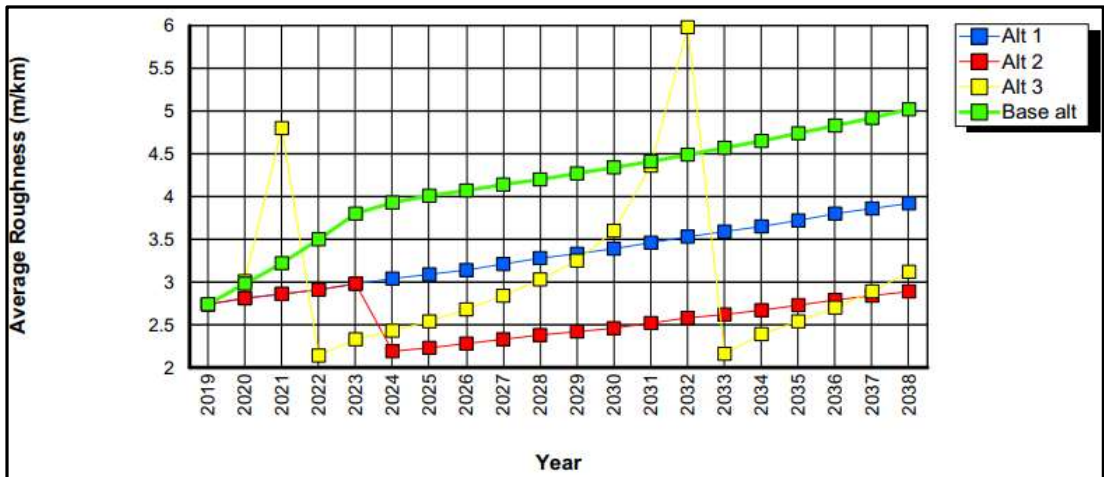


Figure 4.51 Average Roughness Trend of NH-14GJ (KM 380.6-379.6) for Maintenance Standards

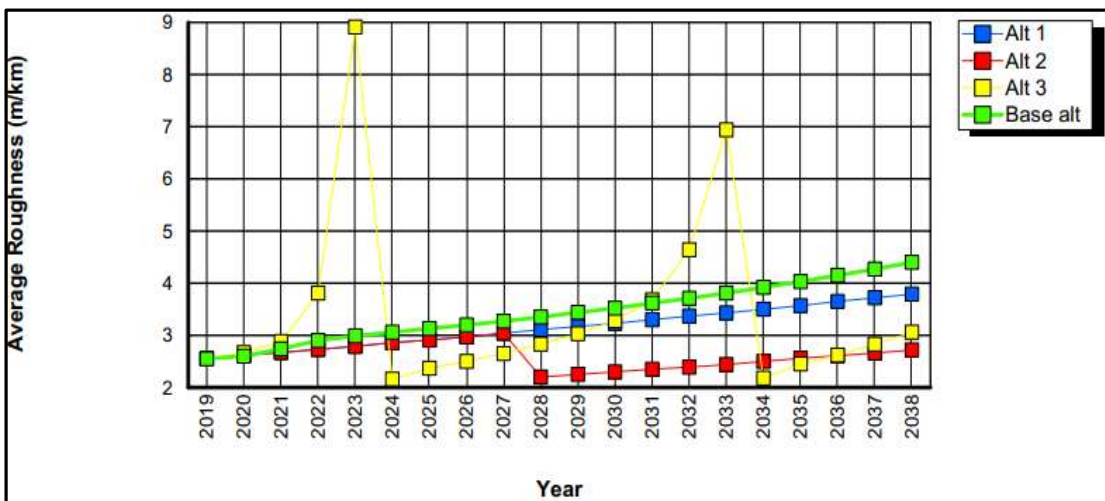


Figure 4.52 Average Roughness Trend of NH-2UP 01 for Maintenance Standards

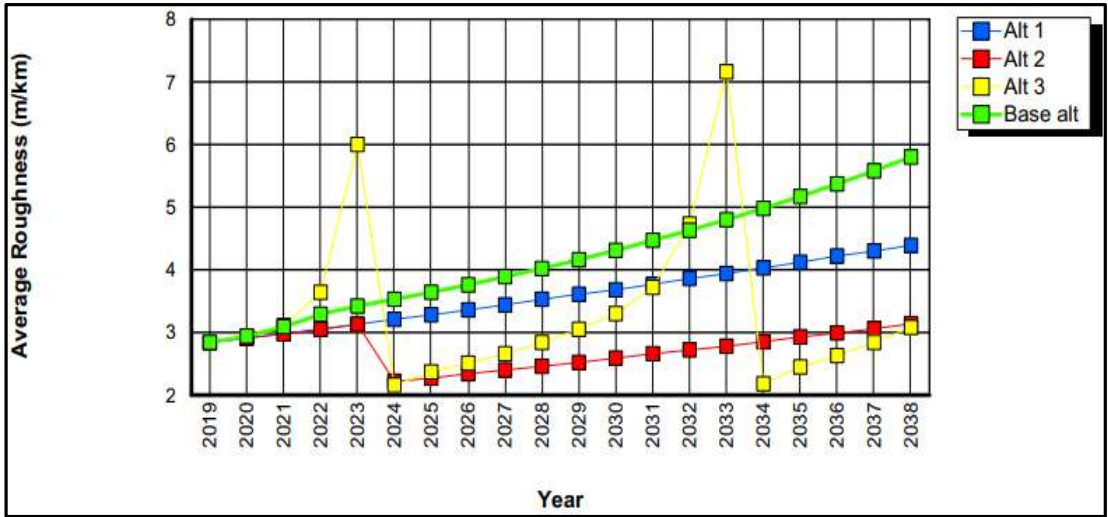


Figure 4.53 Average Roughness Trend of NH-2UP 02 for Maintenance Standards

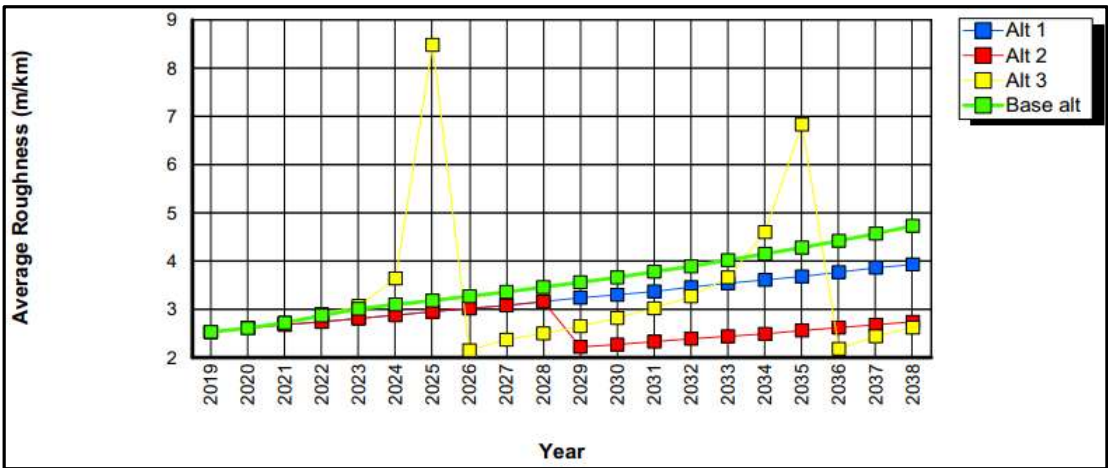


Figure 4.54 Average Roughness Trend of NH-37AS (Km 177.30-178.30) for Maintenance Standards

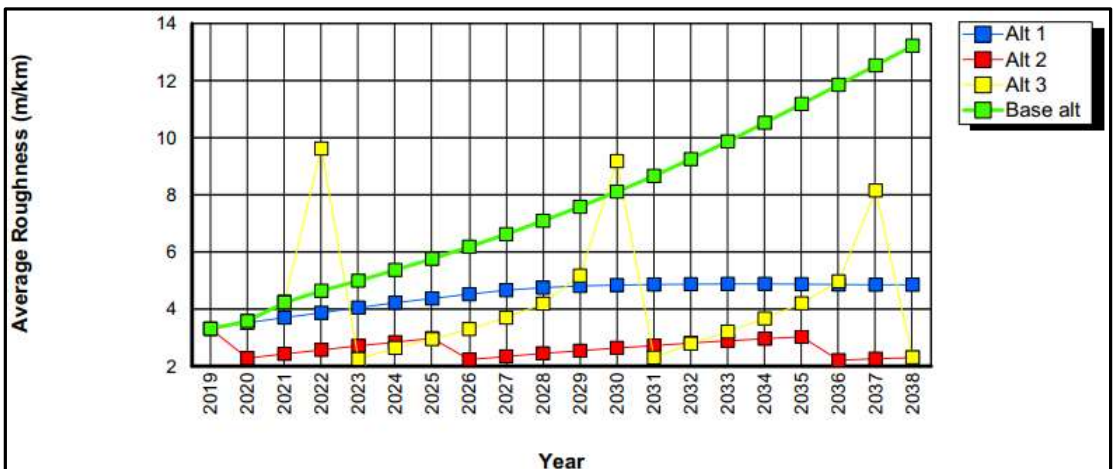


Figure 4.55 Average Roughness Trend of NH-4 KA01 (KM 46-45) for Maintenance Standards

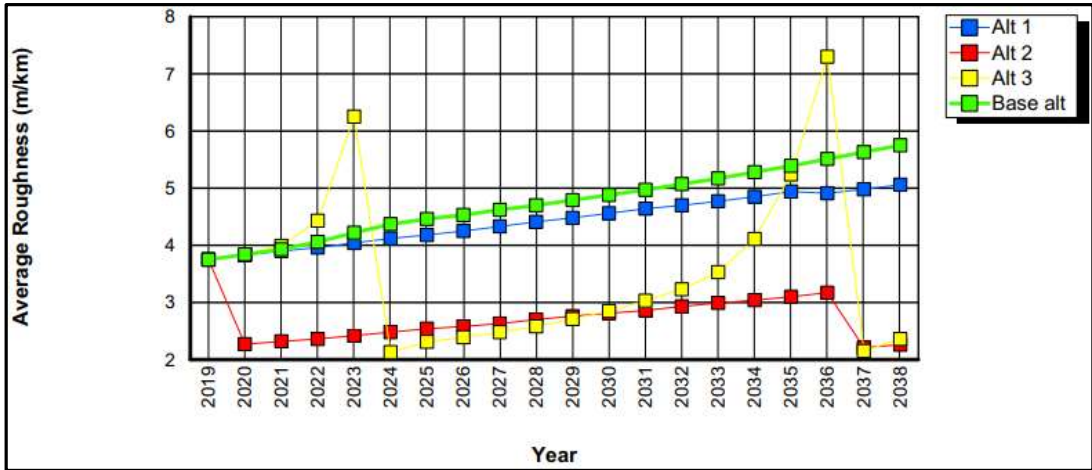


Figure 4.56 Average Roughness Trend of NH-4 KA 02 (KM 481-482) for Maintenance Standards

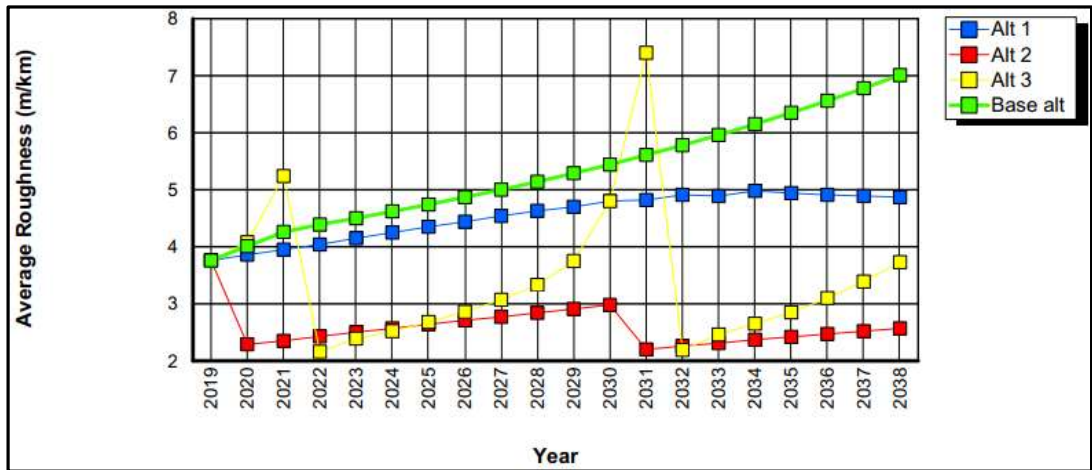


Figure 4.57 Average Roughness Trend of NH-4 KA03 (KM 82-83) for Maintenance Standards

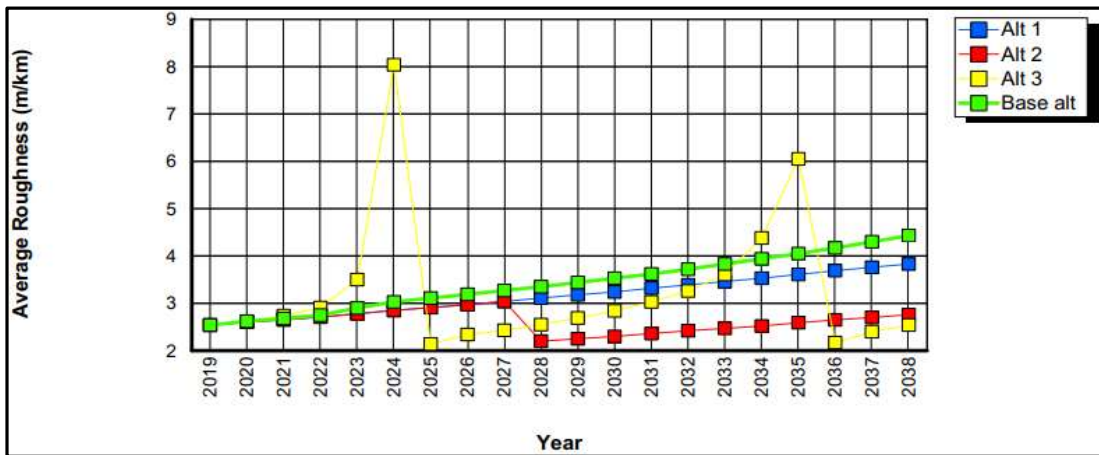


Figure 4.58 Average Roughness Trend of NH-5 AP01 (Km 691.25-690.75) for Maintenance Standards

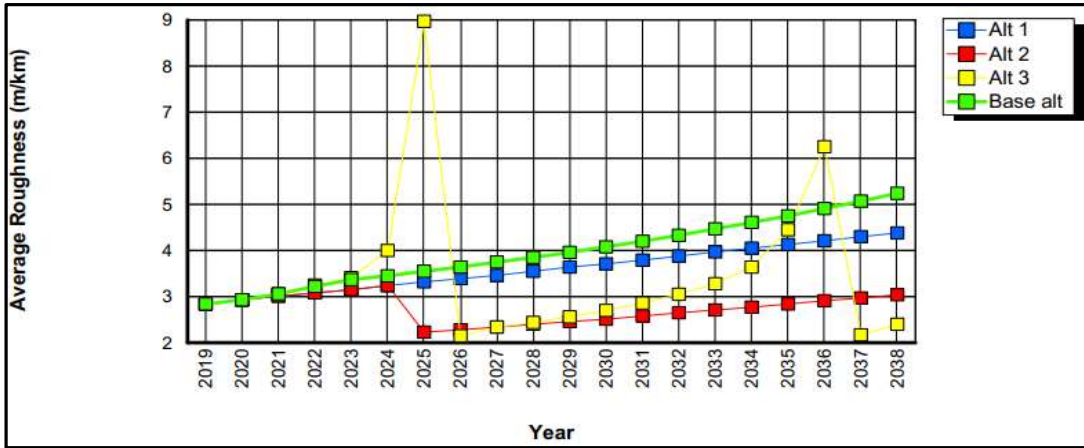


Figure 4.59 Average Roughness Trend of NH-5 AP02 (KM 698.6-698.1) for Maintenance Standards

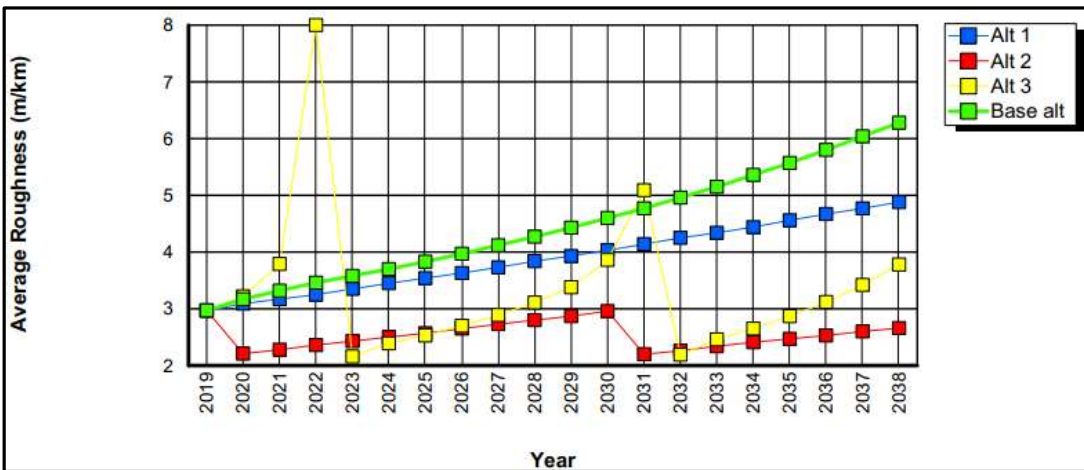


Figure 4.60 Average Roughness Trend of NH-5 AP03 (KM 7.5-7) for Maintenance Standards

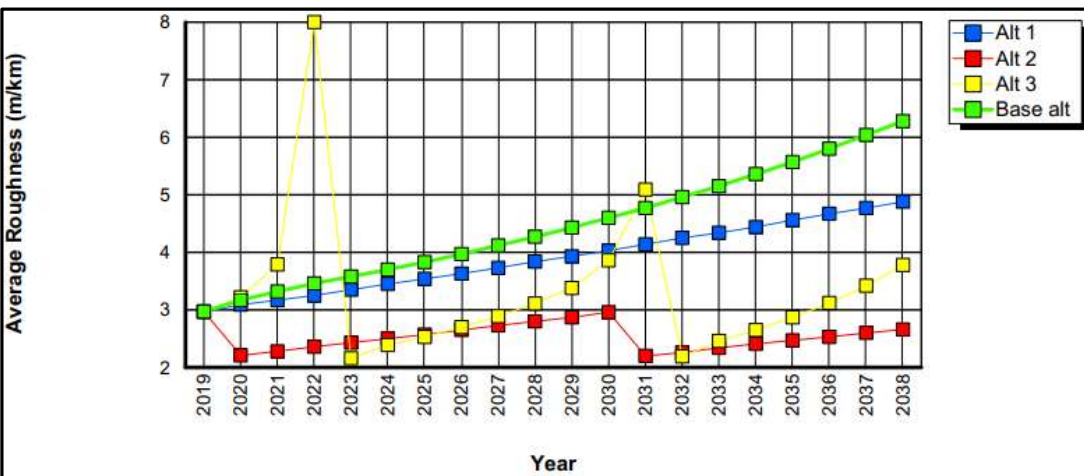


Figure 4.61 Average Roughness Trend of NH-5 AP04 (KM 9.8-9.3) for Maintenance Standards

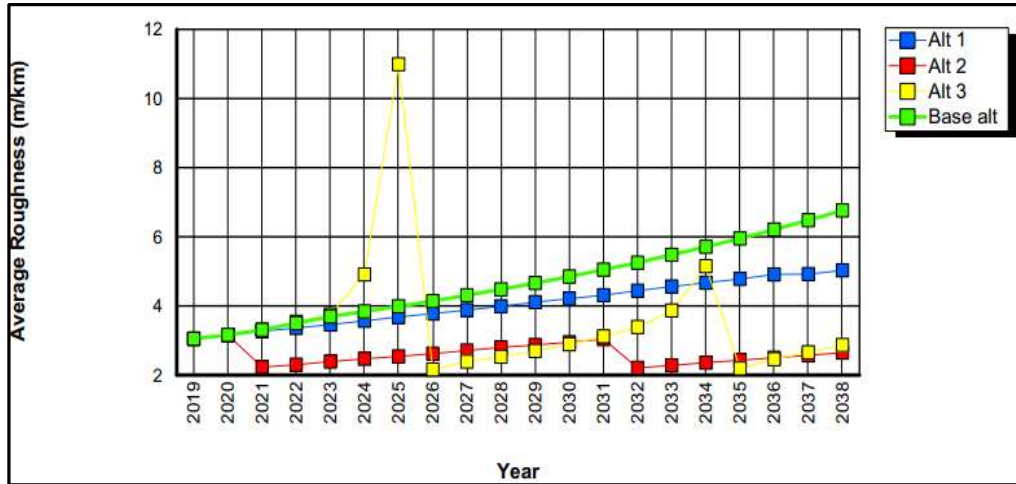


Figure 4.62 Average Roughness Trend of NH-4 MH01 (KM 539-538) for Maintenance Standards

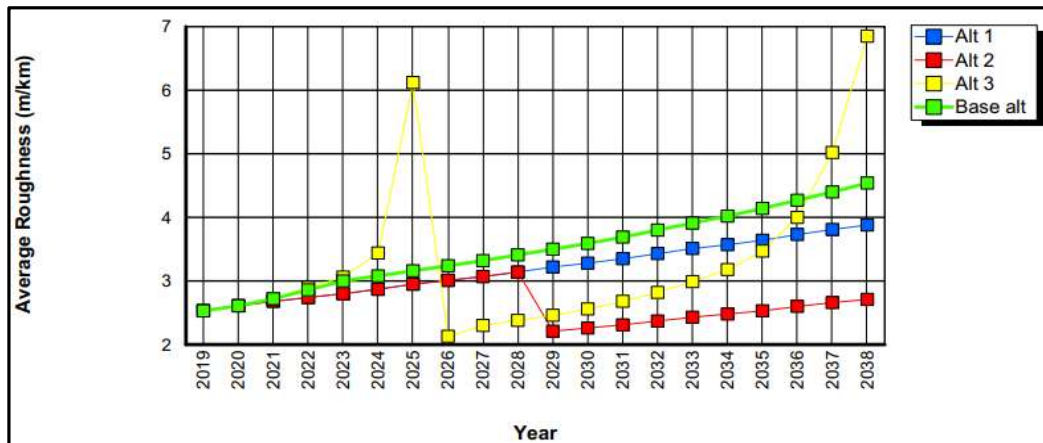


Figure 4.63 Average Roughness Trend of NH-7 MH02 (KM 84.2-84.7) for Maintenance Standards

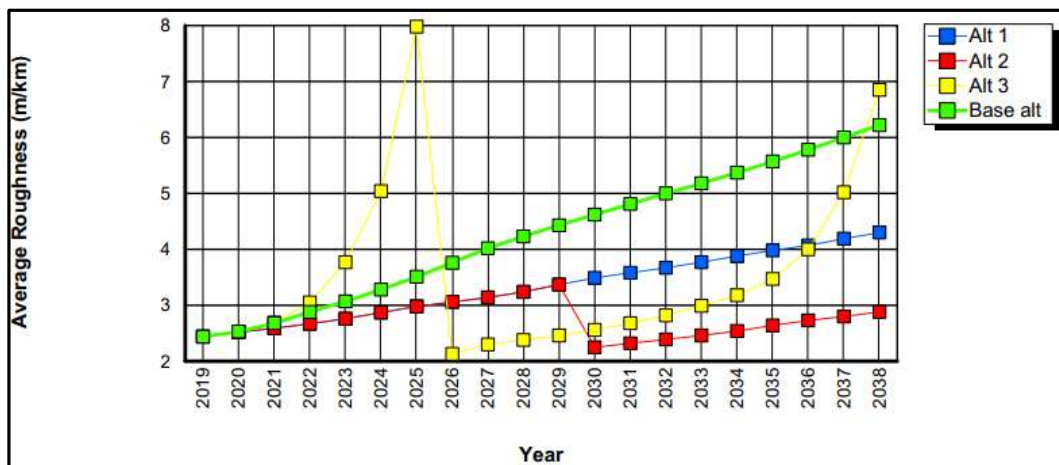


Figure 4.64 Average Roughness Trend of NH-7 MH03 (KM 95.6-96) for Maintenance Standards

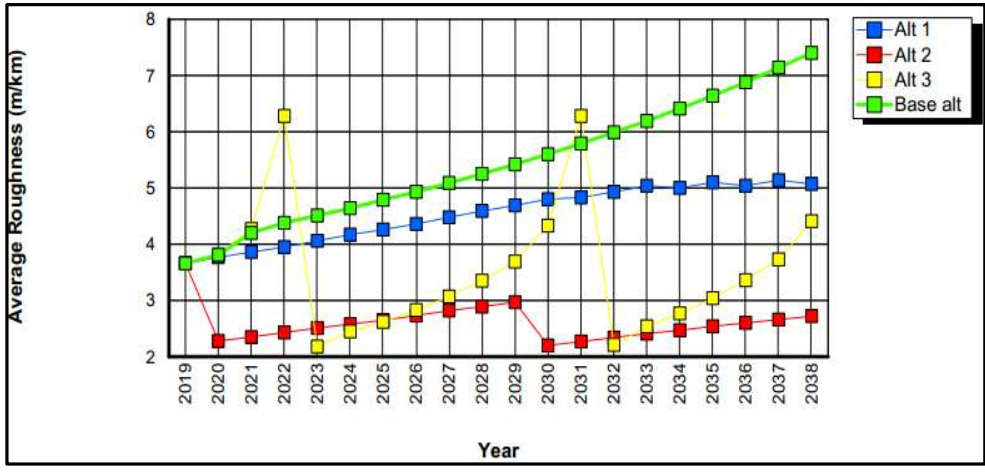


Figure 4.65 Average Roughness Trend of NH-73 01 (KM 0-11) for Maintenance Standards

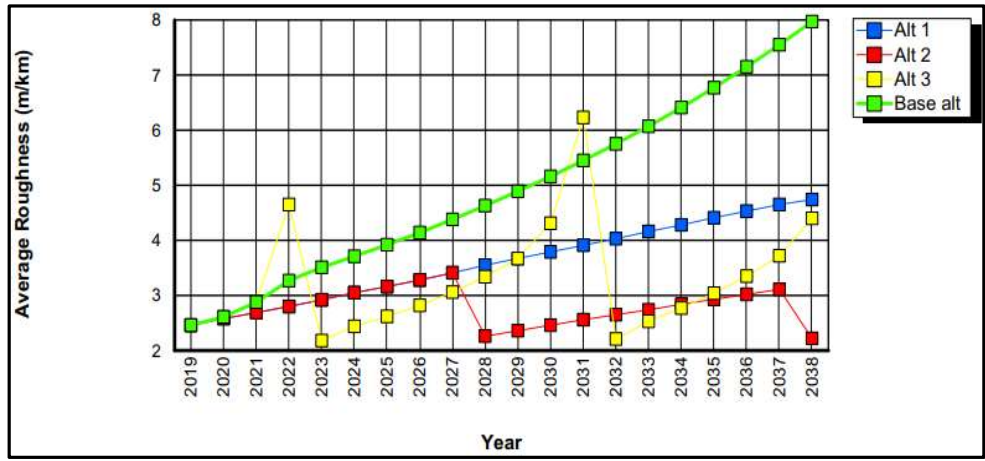


Figure 4.66 Average Roughness Trend of NH-73 02 (KM 11-25) for Maintenance Standards

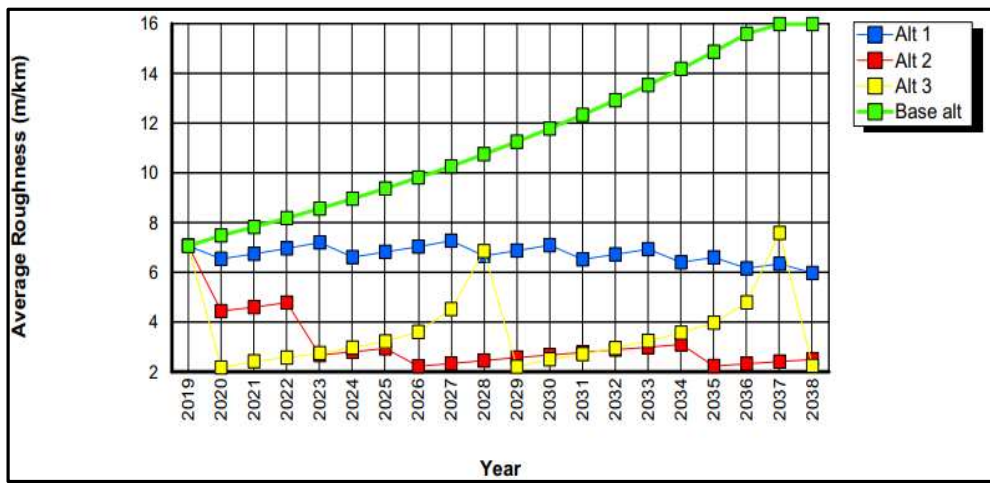


Figure 4.67 Average Roughness Trend of NH-73 03 (KM 25-35) for Maintenance Standards

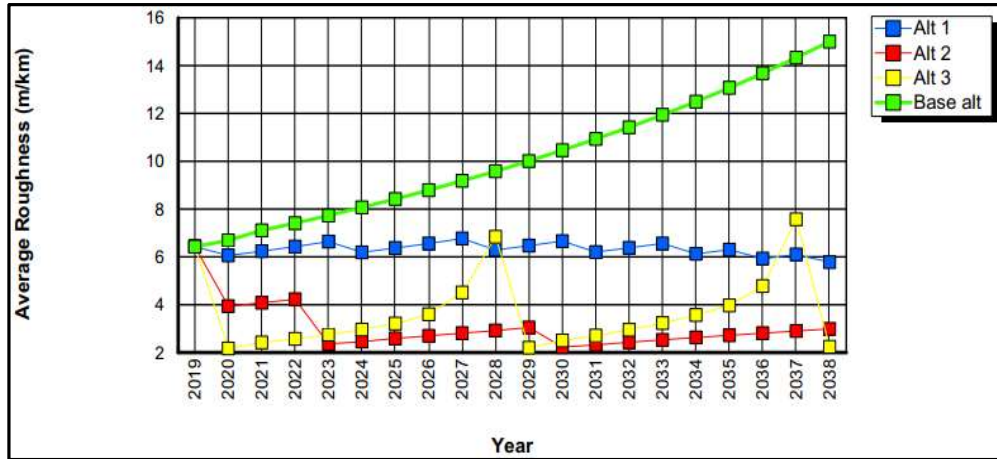


Figure 4.68 Average Roughness Trend of NH-73 04 (KM 35-47) for Maintenance Standards

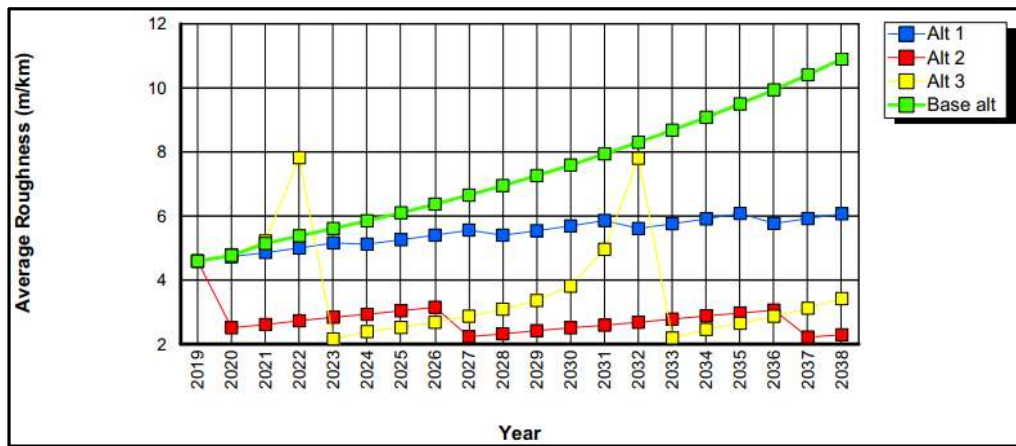


Figure 4.69 Average Roughness Trend of NH-74 01 (KM 0-13) for Maintenance Standards

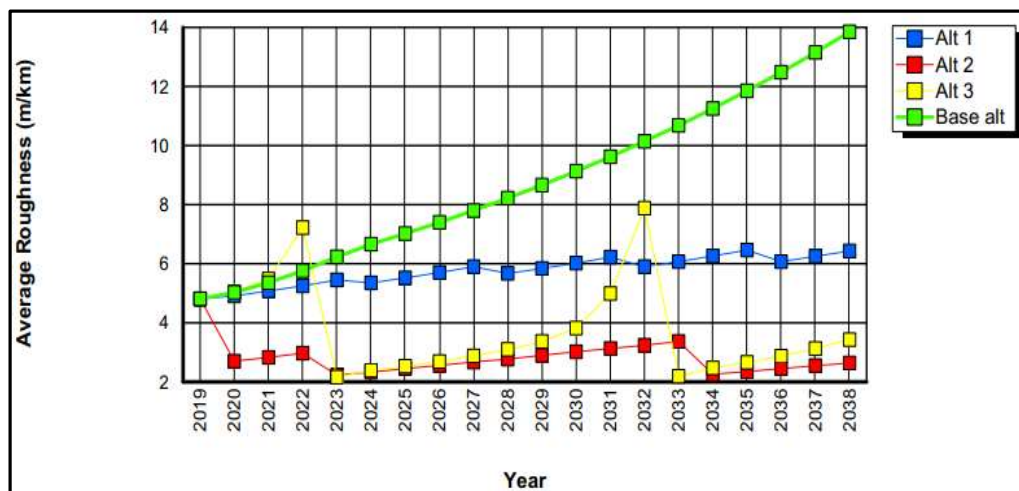


Figure 4.70 Average Roughness Trend of NH-74 02 (KM 13-30) for Maintenance Standards

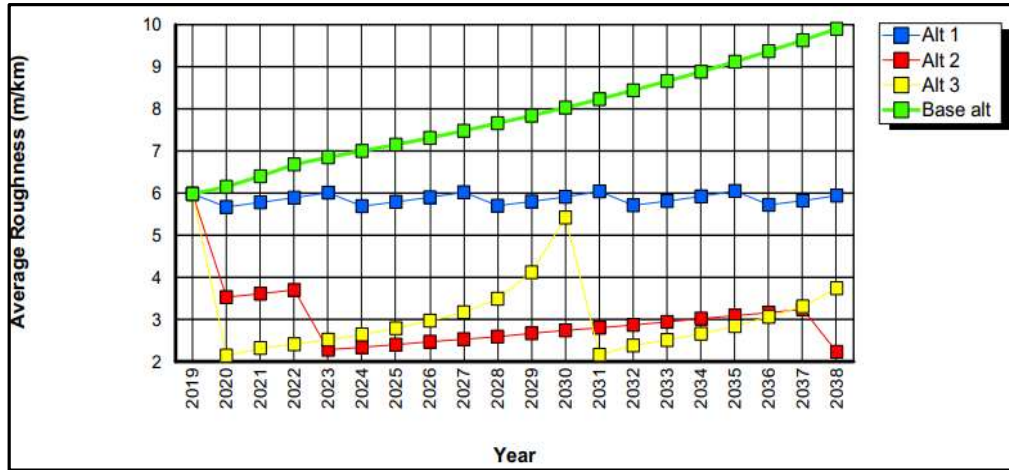


Figure 4.71 Average Roughness Trend of NH-72 01 (KM 105-118) for Maintenance Standards

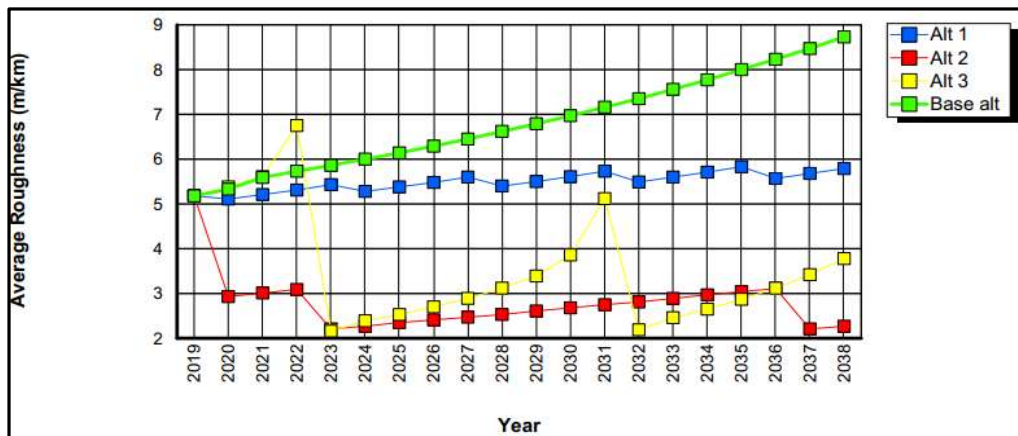


Figure 4.72 Average Roughness Trend of NH-72 02 (KM 118-132) for Maintenance Standards

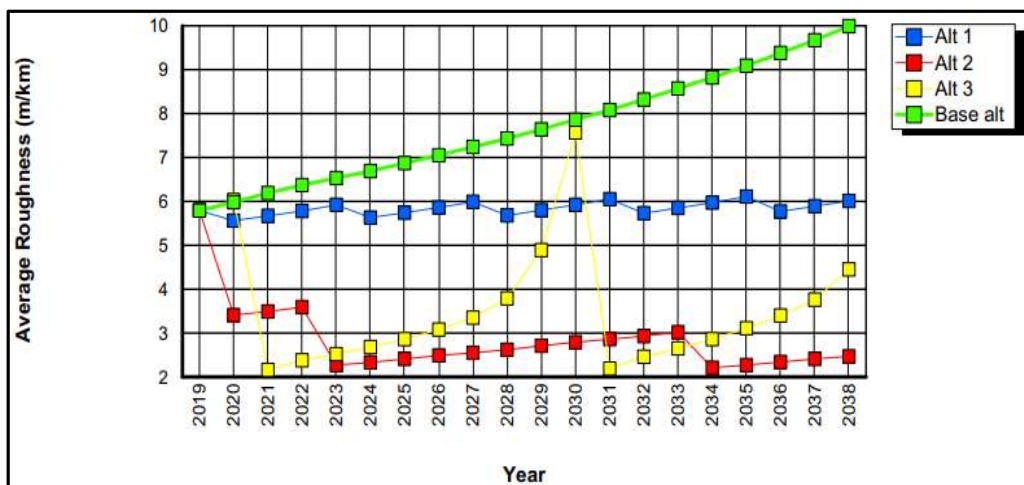


Figure 4.73 Average Roughness Trend of NH-72 03 (KM 132-148) for Maintenance Standards

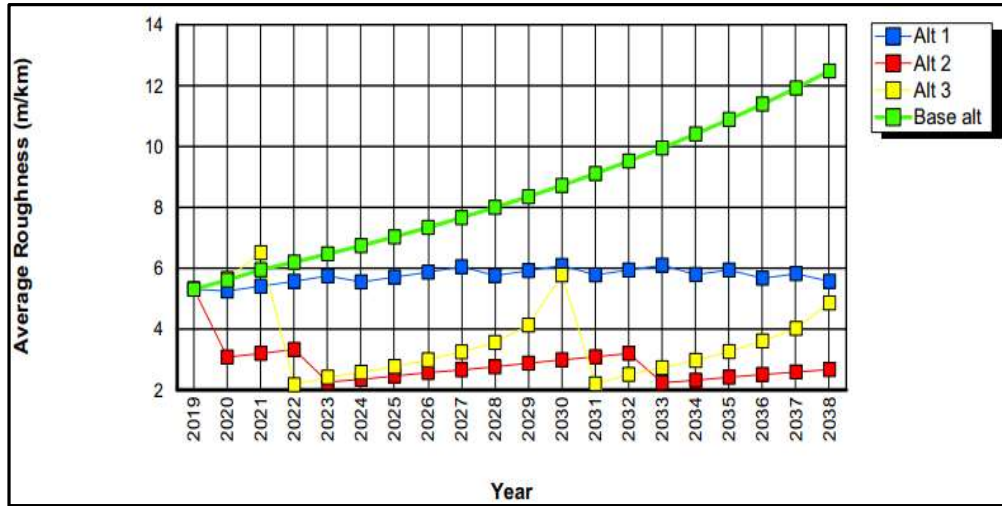


Figure 4.74 Average Roughness Trend of NH-72 04 (KM 162-180) for Maintenance Standards

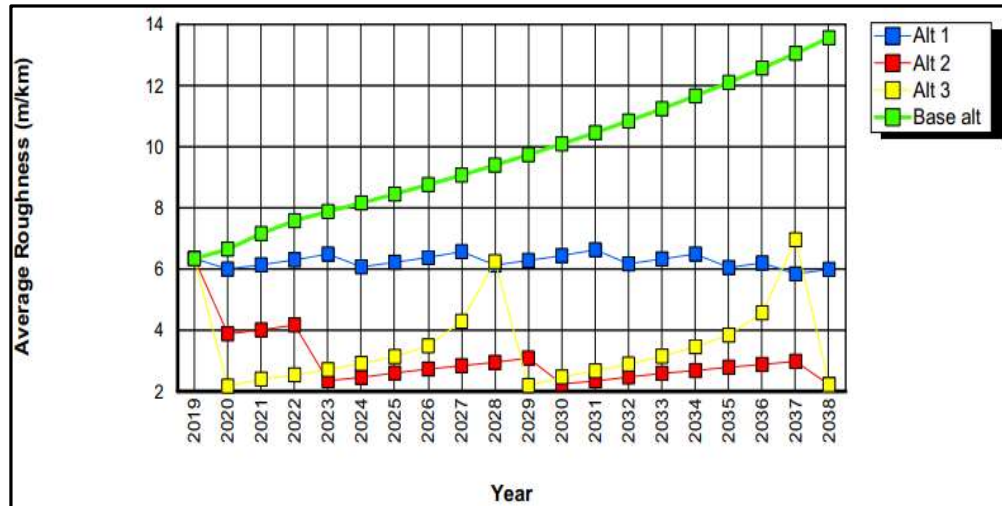


Figure 4.75 Average Roughness Trend of NH-72 05 (KM 180-197) for Maintenance Standards

Comments: It can be observed from the above graphs that maintenance alternatives have been correctly triggered corresponding to the intervention limits established for the entire NH road network for the analysis period of 20 years. In some of the road sections Alternative 3 i.e., Major Overlay intervenes at roughness value much higher than the specified critical limit (IRI > 6 m/km) due to the ‘AND’ condition imposed as the total damaged area limit of 20% has not been exceeded. Therefore, the maintenance work operation will come into effect only when both the intervention criteria have been surpassed at the same instance.

CHAPTER – 5

DEVELOPMENT OF PREDICTION MODELS USING GENETIC PROGRAMMING SYSTEM

5.1 GENERAL

Pavement deterioration prediction models have been developed in this study using Genetic Programming (GP). Four distress models have been generated using GP to predict pavement distresses viz. cracking, ravelling, rutting and roughness for the National Highway road network. Development of this model will assist the road agencies in planning a structured road management program with cost effective solutions for preservation of pavement service life and providing a reliable road network to the users. Genetic programming has been performed using GP KERNEL software program to develop prediction models for the specified NH network. Statistical evaluation of GP model has been done by regression analysis technique by checking the goodness of fit between the predicted and observed roughness values.

5.2 SYSTEMATIC APPROACH OF GP

GP is a domain-independent method which on the Darwinian principles of randomly occurring operations creates an automatic working computer program of new generation to solve problems by genetic mutation of population of computer programs. The whole process involves numerous iterations of input population using the analogy of genetic operations such as mutation, crossover, reproduction, gene deletion and duplication. The five paramount steps required to generate GP model are to (a) specify parameters of the various terminals of stem linked with the program to be developed; (b) specify basic functions for stem of the program to be developed; (c) specify the accuracy measure; (d) set the conditions required prior to running the program; and (e) fix criteria for termination and classification of results obtained from the run. Figure 5.1 illustrates five fundamental steps required for the development of GP model. The input framework comprises of the preliminary conditions (depicted at top of figure) which the user has to specify prior to the run and the desired computer program (depicted at the bottom) is obtained as an output of this genetic programming system.

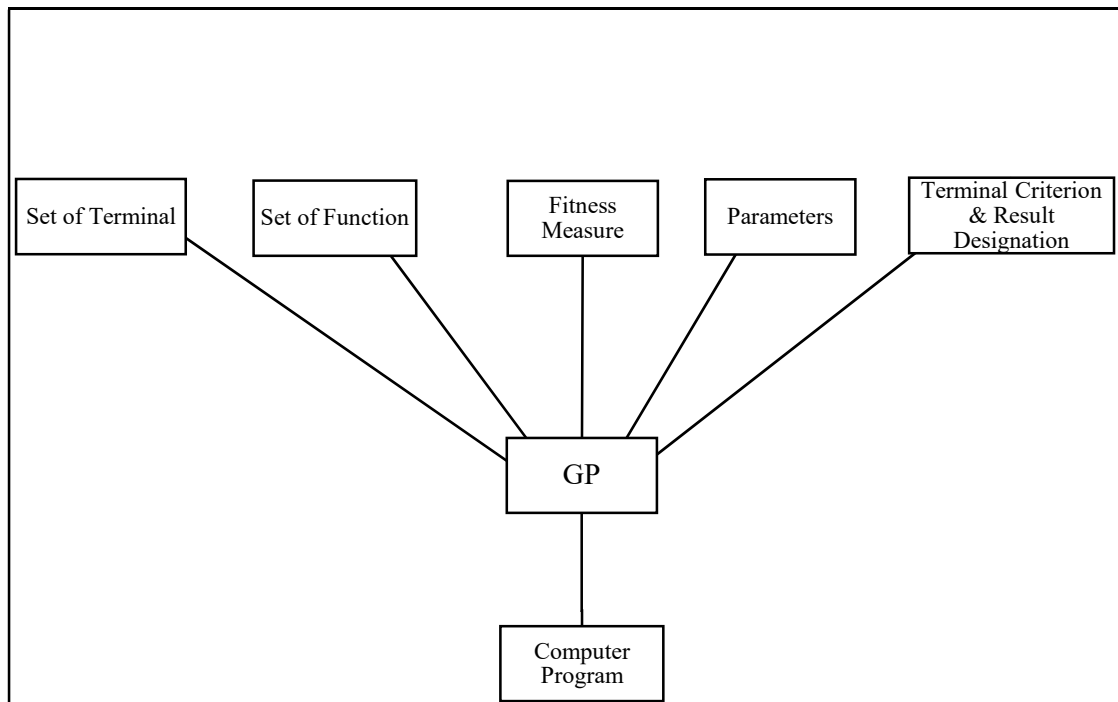


Figure 5.1 Fundamental Steps to generate GP Model

Procedure to perform genetic programming:

- 1) Define initial population (generation 0) of the selected dataset along with their available terminals and functions.
- 2) The following steps (referred to as generation) have been repeatedly performed on population before accomplishing the termination criterion.
 - a) Implementation of problem's fitness measure for execution of individual programs within the population and determine its fitness.
 - b) Selection of individual program(s) (one or two) from the population on the basis of fitness and allow participation in genetic operations.
 - c) For the creation of new individual programs(s) various genetic operations are involved:
 - (i) **Reproduction:** Copying the candidate individual program to new population.
 - (ii) **Crossover:** Recombination of stochastically chosen parts of two selected programs to derive a new offspring program.
 - (iii) **Mutation:** This operation includes creation of new offspring program by random alteration of a stochastically chosen part of single selected program.

(iv) Architecture-altering operations: It includes selection and implementation of one architecture-altering operation to create single new offspring program from the available collection of these operations and targeting one selected program.

3) The single optimal program in population generated during run is garnered and labelled as best possible result and thereby solving the problem.

Table 5.1 depicts the anatomy of GP model comprising of values of the significant input parameters which have been considered in the programming system.

Table 5.1 GP Model Architecture

Parameters	Values	Description
Initial population size	Dataset	Dataset-1 consists of physical attributes of 23 road sections collected in 2011 and 2012
Function set		Function sets used
Training percentage	exp(), sqrt(), tanh(), log(), pow(x,y), +, -, /, *	–
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	250	Population size
λ	150	No. of children produced
Fitness functions	R^2	Coefficient of Determination
	RMSE	Root Mean Square Error

5.3 DEVELOPMENT OF DISTRESS MODELS

In the present study, four distress models linked to National Highway network have been generated using genetic programming system. The control parameters have been thoroughly scrutinized and the values illustrated in Table 5.1. The input population to

the computer program consists of dataset pertaining to physical characteristics of candidate road sections such as pavement condition, pavement age, traffic (AADT). The dataset congregated is of two consecutive years i.e. 2011 and 2012 and modelling of this training dataset has been done using GP to predict pavement distresses for the year 2012. GP gives numerous prediction equations depending upon the attributes of framework in which it has run and based upon fitness measure (such as R^2 and RMSE) the best possible prediction model has been selected corresponding to various distresses as shown in Table 5.2.

Table 5.2 Pavement Deterioration Prediction Models for National Highway Roads

Distress Models	GP Equations
Cracking	$CA_j = (\text{sqrt}(\text{(((sqrt}(\text{(((sqrt}(\text{exp}(\text{age})) * \text{BBD}) * \text{BBD}) * \text{sqrt}(\text{sqrt}(\text{CA}_i) * \text{sqrt}(\text{BBD} * \text{BBD})))))) + \text{sqrt}(\text{BBD} * \text{log}(\text{((traffic} / \text{age}) + (\text{CA}_i * \text{CA}_i)))))) * \text{sqrt}(\text{CA}_i) * \text{sqrt}(\text{exp}(\text{BBD})))) + \text{CA}_i)$
Ravelling	$RAV_j = (((\text{log}(\text{age}) * \text{tanh}(\text{tanh}(\text{RAV}_i * (\text{tanh}(\text{log}(\text{tanh}(\text{tanh}(\text{tanh}(\text{tanh}(\text{tanh}(\text{exp}(\text{tanh}(\text{RAV}_i) - \text{tanh}(\text{pow}(\text{traffic}, 2)))))))))) + \text{RAV}_i))) * \text{RAV}_i)) + \text{RAV}_i) + (\text{log}(\text{age}) * \text{tanh}(\text{tanh}(\text{tanh}(\text{tanh}(\text{RAV}_i * \text{RAV}_i)) * \text{age})) * \text{RAV}_i))$
Rutting	$RUT_j = (RUT_i + \text{tanh}(\text{tanh}(\text{tanh}(\text{tanh}(\text{pow}(\text{tanh}(0.37790966) + \text{exp}(\text{((tanh}(\text{exp}(\text{sqrt}(\text{sqrt}(\text{BBD}))) * \text{exp}(\text{BBD} * \text{age})))) - \text{tanh}(\text{tanh}(\text{tanh}(\text{RUT}_i) / \text{exp}(\text{BBD})))) * (\text{BBD} - \text{exp}(\text{sqrt}(\text{pow}(\text{BBD} / \text{traffic}, 2))))), 2))))))$
Roughness	$IRI_j = (IRI_i - ((IRI_i + (IRI_i - (-3.174337\text{e-}002 * ((1.41491628 - (IRI_i + (((IRI_i + IRI_i) - IRI_i) + \text{sqrt}(\text{sqrt}(\text{IRI}_i)))))) + (IRI_i - (\text{pow}(-0.3, 2) * ((\text{sqrt}(\text{traffic}) + (\text{age} + \text{pot hole})) * -3.31783\text{e-}002)))))) * -3.273277\text{e-}002))$

5.4 VALIDATION OF GP MODEL

To check the adequacy and reliability of these distress models, validation dataset of year 2012 has been used and goodness of fit of these models measured simply by plotting scatter graphs between observed distress values and predicted distress values. Validation is essential as it examines the applicability of model for the particular conditions. It can be observed from post-regression results shown from Figure 5.2 to Figure 5.5 that there is slight difference between the observed values and predicted values. This difference is quiet rational due to the variation in physical characteristics such as pavement history, traffic conditions, geographical locations of selected NH road sections. Also due to the modelling technique adopted and certain assumptions like normal construction quality of bituminous surfacing at optimum conditions has led to noticeable deviation in this quantitative assessment of distress models. Table 5.3 depicts the physical characteristics of road sections having individual road length 1 km gathered for validation dataset.

Table 5.3 Validation Dataset

S. No.	Sections	Age	Traffic (AADT)	Crack (%)	Ravel (%)	Pothole (%)	Rut depth (mm)	Roughness (m/km)
1	NH-58 01	7	11450	5.66	2.12	0	2.55	2.09
2	NH-58 02	9	11370	8.63	3.55	0	4	2.6
3	NH-58 03	9	12290	5.12	6.13	0	3.19	2.59
4	NH-58 04	9	13980	14.5	2.12	0	2.72	2.61
5	NH-58 05	9	13860	28.09	6.13	2.57	2.81	2.77
6	NH-58 06	11	11260	8.93	6.13	2.98	3.49	2.56
7	NH-58 07	11	8540	6.87	6.13	0	3.12	2.95
8	NH-58 08	11	6798	2.75	13.25	1.12	2.46	2.54
9	NH-58 09	9	6798	10.1	7.3	0	3.27	3.29
10	NH-58 10	9	6798	10.22	7.3	0	2.31	3.79
11	NH-58 11	9	6798	23.47	10.93	0	4.09	3.9
12	NH-58 12	9	6798	2.3	12.1	0	2.09	3.09

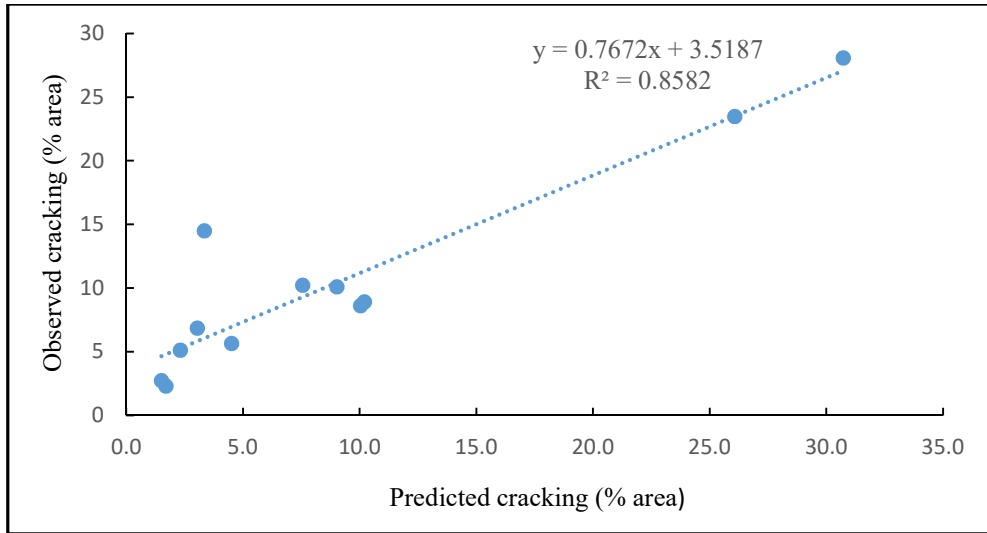


Figure 5.2 Validation of Cracking Model

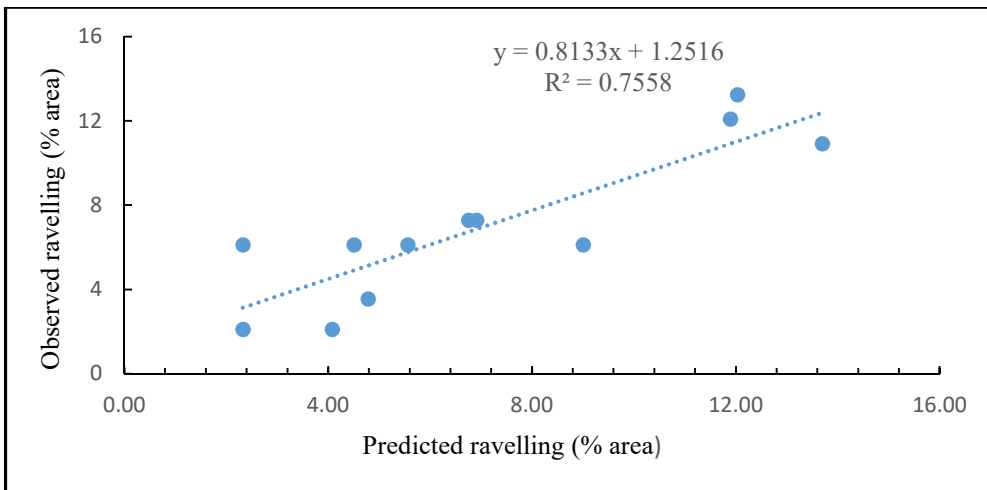


Figure 5.3 Validation of Ravelling Model

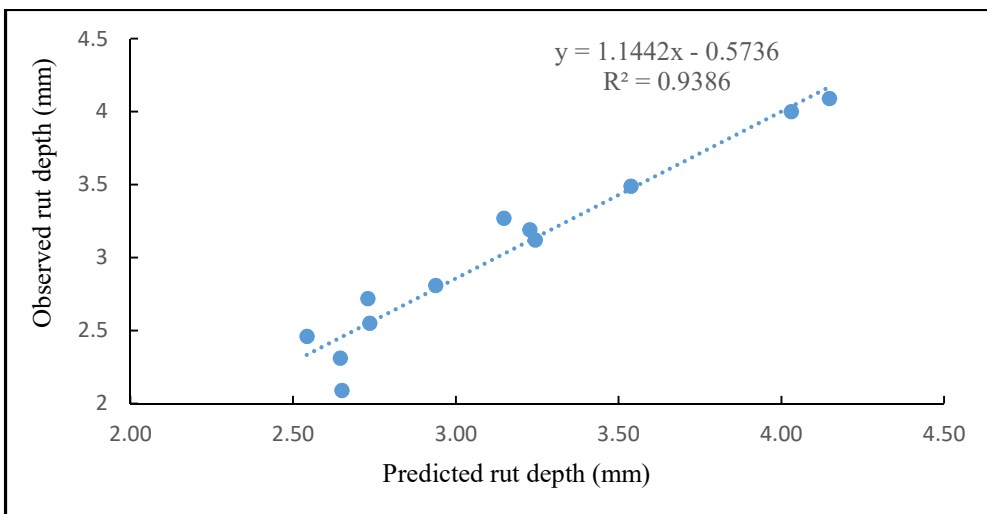


Figure 5.4 Validation of Rutting Model

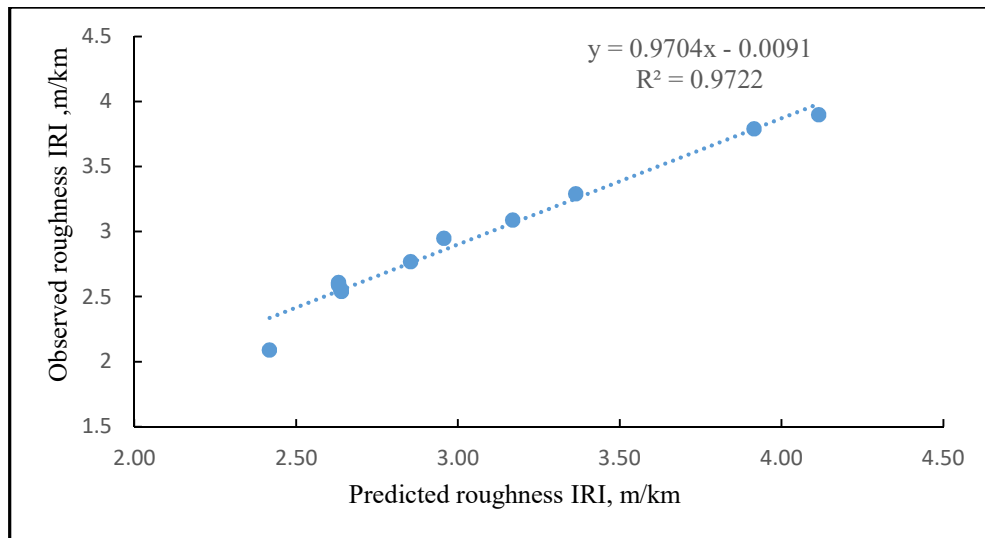


Figure 5.5 Validation of Roughness Model

Table 5.4 depicts the post-regression results in terms of coefficient of determination (R^2) and root mean square error (RMSE) related to various distress models which indicate the adequacy of GP models.

Table 5.4 Post-Regression Results

S. No.	Distresses Models	Linear Regression Model	R^2	RMSE
1	Cracking	$y=0.7672x+3.5187$	0.8582	0.347
2	Ravelling	$y=0.8133x+1.2516$	0.7558	0.148
3	Rutting	$y=1.1442x-0.5736$	0.9386	0.054
4	Roughness	$y=0.9704x-0.0091$	0.9722	0.024

Statistical evaluation of roughness prediction model obtained using GP has been done using students t-test to determine the statistical significance i.e. difference between the predicted roughness values and observed roughness values. The ‘null hypothesis’ used in t-test states that there is no difference between the observed and predicted values for the given dataset. From the Table 5.5 it has been observed that the t-value is less than critical values but $p > 0.05$ which rejects the null hypothesis and proves that the predictions made by the model are accurate. Table 5.5 depicts the statistical evaluation results obtained after performing student’s t-test.

Table 5.5 t-test: Paired Two Sample for Means

	Observed IRI	Predicted IRI
Mean	2.950	2.935
Variance	0.191	0.217
Observations	18	18
Pearson Correlation	0.978	
Hypothesized Mean Difference	0	
df	17	
t Stat	0.664	
P(T<=t) one-tail	0.257	
t Critical one-tail	1.739	
P(T<=t) two-tail	0.515	
t Critical two-tail	2.109	

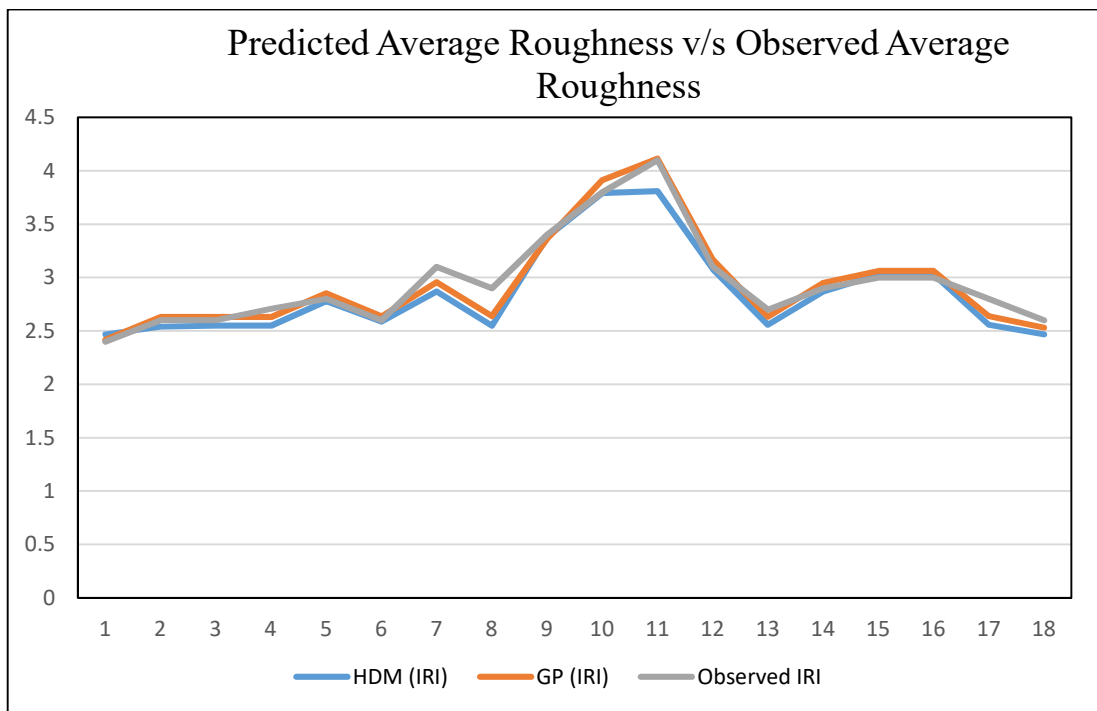
5.5 COMPARATIVE ANALYSIS

A comparison has been done to analyse the capabilities of the two prediction models i.e., HDM-4 and GP in terms of the roughness parameter for the candidate road sections. Figure 5.6 depicts graphical representation of predicted roughness values using both HDM-4 and GP models which have been compared with the observed field values for all the road sections. It can be concluded that there is marginal variation in predicted roughness values mainly due to the difference in the architecture and working principles of these two software programs. Also it has been observed that the fitness of GP model increases with incorporation of more control parameters affecting pavement performance. Therefore, it shows that there is no such restriction on consideration of significant input parameters for analysis in GP. Table 5.6 depicts the variation in prediction capabilities of HDM-4 and GP models for individual road section and results indicate that HDM model is slightly more accurate prediction model than GP model.

Table 5.6 Variability of Models in terms of Roughness Prediction

Sections	HDM variability (%)	GP variability (%)
NE-1GJ01	1.47	1.41
NE-1GJ02	1.54	1.63
NE-1GJ03	1.55	1.63
NE-1GJ04	1.55	1.63

NH-14GJ05	1.78	1.85
NH-2UP01	1.59	1.63
NH-2UP02	1.87	1.95
NH-37AS01	1.55	1.64
NH-4KA01	2.38	2.36
NH-4KA02	2.79	2.91
NH-4KA03	2.81	3.11
NH-4MH01	2.08	2.16
NH-5AP01	1.56	1.63
NH-5AP02	1.87	1.95
NH-5AP03	2.03	2.06
NH-5AP04	2.03	2.06
NH-7MH02	1.56	1.63
NH-7MH03	1.47	1.53



**Figure 5.6 Comparison of HDM and GP model in terms of Roughness (IRI)
Prediction Capabilities**

CHAPTER – 6

ECONOMIC ANALYSIS

6.1 GENERAL

Efficient and smart pavement management system should target monitoring, maintenance and timely upgradation of existing road network along with socio-economic benefits. Longevity and durability of road pavements to cater the projected traffic loading should be an integral part of the framework of any road appraisal system adopted. Optimum maintenance solutions should not only be performance specific but should be cost effective as well. The main concern for road agencies is availability of adequate funds for road maintenance projects at all time. Any delay in allocation of maintenance funds will degrade pavement service quality and consequently increase the road user cost. The main objective of this study is to predict a cost effective maintenance solution to the National Highways of India for preservation of pavement service life. Most appropriate maintenance strategy has been determined on the basis of cost comparisons of various M&R strategies assigned to the identified NH road network. The effectiveness of a treatment work depends upon the timing and intervention limits throughout the pavement life cycle.

6.2 SALIENT FEATURES

Economic cost – In this study we are only concerned with the economic cost related to the road management of NH network. For any road project, the material cost, labour cost, machinery cost, surplus cost incurred excluding the taxes, duties and subsidies represents economic cost. Financial cost (market cost) represents the total market cost inclusive of tariffs which the organisation has to bear. In terms of the current economic scenario of country, economic cost represents the true project cost which should be considered for economic appraisal of any road project.

Discount rate – It is defined as the rate of interest at which future expenditure costs and savings (benefits) are decreased to equivalent values at common time. Appropriate selection of discount rate brings out realistic economic appraisal of road project. It should be kept in mind that the discount rate to be adopted for any road project should not be less than the market interest rate. A discount rate of 12% has been taken in the study in compliance with the Planning Commission guidelines mentioned in IRC SP:30-2009.

Net Present Value – NPV is the most powerful criteria for evaluating the economic efficiency of maintenance alternatives. Maintenance alternative having highest NPV value is defined as optimum work alternative for the road project. Budget prioritization i.e., establishing a priority order of road sections to which the budget will be allocated for the intervention of optimum M&R strategy can be achieved using this economic parameter. Road management plan proposed comes with certain intensity of future discounted costs and benefits. Benefits correspond to the savings in both road agency cost and user cost (RUC). NPV represents the difference between the present value of benefits and present value of costs associated with project.

Internal Rate of Return - This criterion describes the interest rate at zero NPV i.e. when present cost value equalizes present benefits. Positive NPV indicates higher economic benefits in terms of agency cost and user cost and hence leads to high value of IRR which is always desirable. A road project is economically viable if the IRR value exceeds the interest rate obtained from investment in open market.

Benefit Cost Ratio – measures the value of benefits attained from capital cost invested in the project. It is defined as the dimensionless ratio of benefits acquired to the cost invested by the road agency.

6.3 METHODOLOGY

Economic analysis has been conducted to determine the most appropriate maintenance strategy suitable for the identified road network. Project analysis application has been used to perform the life cycle cost analysis. The primary component of RUC i.e., VOC has been considered in the analysis. To estimate the economic efficiency of any proposed maintenance work alternatives we require cost data pertaining to vehicle cost and maintenance cost. Economic costs data for the various maintenance works assigned to the road network have been gathered and revised till date. CRRI has given mathematical equation for annual updation of economic costs (MORT&H 2001b) which incorporates the labour cost, material cost and fuel cost to determine the increment in cost from the base year (1999-2000) till date. Chopra et al. calculated economic cost of maintenance works using the CRRI equation applicable for Urban road network for the year 2016. An annual inflation rate of 8% has been considered to update the available cost data to the present year. Financial cost has been estimated from calculated economic cost using a factor of 0.85 as suggested in IRC: SP: 30-2009. Table 6.1 depicts updated

economic and financial costs of various work operations/activities assigned to the road network.

Table 6.1 Updated Economic Cost of Proposed Maintenance Works

Sr. No.	Work Operations	Economic cost 2016 (Rs/sq. m)	Economic cost 2019 (Rs/sq. m)	Financial Cost (Rs/sq. m)
1	Crack Seal	66.4	83.64	98.4
2	Pothole Patching	84.7	106.70	125.52
3	Double Bituminous Surface Dressing (DBSD)	282.7	356.12	418.96
4	Mix Seal Surfacing	230.6	290.49	341.75
5	Bituminous Concrete (BC 25 mm)	230.6	290.49	341.75
6	Major Overlay (80 mm DBM + 40 mm BC)	1429.8	1801.14	2118.98

Vehicle Operating Costs incorporates cost items such as fuel cost, engine oil cost, maintenance cost etc. which needs to be calculated for the economic analysis. In the present study, VOC components have been equated using the empirical relations suggested by IRC SP: 30-2009 (Annexure C, clause 6.6) and has been shown in detail in Annexure B of this analysis report. The National Highway road network consists of free-flow traffic corridors having four lane road sections and calculations have been done accordingly. Since majority of the road sections fall under plain and rolling terrain, therefore, road geometry parameter of Rise and Fall is assumed to be 1 m/km (Rise = 0.5 m/km and Fall = 0.5 m/km) with average roughness of 2000 mm/km. VOC calculated using the mathematical equations are for highway traffic conditions and therefore the probability of congestion is negligible and so the congestion effect has been ignored. Table 6.2 depicts significant constituents of VOC applicable for the specified road network.

Table 6.2 VOC Parameters for the Highway Traffic Composition

Cost Parameters	Car/Van/jeep	LCV	Bus	Truck	Multi-Axle Truck
New vehicle cost (Rs.)	8,14,907	6,96,998	11,77,200	12,19,275	15,00,000
New Tyre cost (Rs.)	31,493	4975	10,707	11,000	11,500
Free flow speed (km/hr)	77.82	62.28	59.86	55.03	46.23
Fuel cost (litre/1000 km)	34.4	150.25	177.21	140.89	323
Lubrication cost (litre/1000km)	1.88	1.13	1.74	1.85	3.5
Maintenance labour (Rs/km)	0	8.82	24.46	27.69	28.37
Spare parts cost (Rs/km)	0	23.9	44.5	75	76.85
Crew wages (Rs/km)	0	3.64	1.036	1.7	2.26
Utility (km/day)	481	164.6	934.8	352.27	317
Overheads (Rs./km)	0.91	4.67	0.84	2.6	2.89
Annual Interest (%)	8	8	8	8	8

Cost streams for various alternatives have been computed which includes total net benefits in terms of savings in expenditure cost to be incurred by the road agency and reduction in RUC. Table 6.3 represents the total expenditure cost (exclusive of taxes) related to all the selected sections which should be available for timely and proper maintenance throughout the analysis period of 20 years.

Table 6.3 Total Expenditure Cost Corresponding to Individual Maintenance Works to be Incurred by Road Agency

S. No.	Sections	Total Economic costs of proposed M&R works			
		Alternative 1	Alternative 2	Alternative 3	Base alternative
1	NE-1GJ01	17.45	11.325	25.216	0.202
2	NE-1GJ02	14.957	8.096	25.216	0.204
3	NE-1GJ03	14.957	8.096	25.216	0.202
4	NE-1GJ04	14.95	9.71	25.216	0.205
5	NH-14GJ05	12.464	11.35	25.216	0.219
6	NH-2UP01	12.46	12.96	25.216	0.236
7	NH-2UP02	12.46	14.57	25.216	0.207
8	NH-37AS01	12.46	12.96	25.216	0.18
9	NH-4KA01	42.37	29.15	37.82	0.2
10	NH-4KA02	12.46	12.96	25.21	0.209
11	NH-4KA03	27.42	17.83	25.21	0.23
12	NH-5AP01	7.47	6.48	12.6	0.101
13	NH-5AP02	14.95	12.96	25.21	0.177
14	NH-5AP03	7.47	8.109	12.6	0.117
15	NH-5AP04	7.47	8.109	12.6	0.117
16	NH-4MH01	12.46	16.21	25.21	0.179
17	NH-7MH02	31.16	32.41	63	0.451
18	NH-7MH03	6.23	4.86	12.6	0.081
19	NH-73 01	191.94	178.4	277.37	2.242
20	NH-73 02	244.29	249.65	353.02	2.879
21	NH-73 03	174.49	96.85	252.16	2.299
22	NH-73 04	209.39	116.22	302.59	2.758
23	NH-74 01	194.44	232.15	327.8	3.033
24	NH-74 02	254.27	358.89	428.67	3.602
25	NH-72 01	162.03	253.13	327.8	3.118
26	NH-72 02	209.39	272.6	353.02	3.253
27	NH-72 03	239.31	311.55	403.45	3.687
28	NH-72 04	314.09	350.49	453.88	4.182
29	NH-72 05	296.64	164.64	428.67	2.902

The economic analysis reports obtained using HDM-4 have been analysed and the NPV/COST parameter has been kept as the indicator to determine the economic efficiency of the proposed alternatives. Timings of various maintenance works has been traced out from these reports which will serve as a future maintenance plan for retarding the rate of pavement deterioration and keeping the road sections in acceptable conditions. Based on the maximum NPV/COST ratio the most effective maintenance solution has been identified for all the road sections. From Table 6.4 it can be concluded that ‘Alternative 3’ which includes ‘Major Overlay (80mm DBM + 40mm BC)’ is the most appropriate maintenance strategy for the entire NH road sections.

S. No.	Sections	M&R Strategy	Intervention year	NPV/COST
1	NE-1GJ01	Alternative 1	2019, 2023, 2027, 2031, 2034, 2036	11.5
		Alternative 2	2019, 2023, 2027, 2030, 2034, 2038	21.99
		Alternative 3	2024, 2035	72
2	NE-1GJ02	Alternative 1	2019, 2025, 2029, 2032, 2035, 2037	18.207
		Alternative 2	2019, 2026, 2031, 2033	36.847
		Alternative 3	2023, 2034	77.169
3	NE-1GJ03	Alternative 1	2019, 2024, 2029, 2032, 2035, 2037	11.579
		Alternative 2	2019, 2025, 2030, 2035, 2038	27.5
		Alternative 3	2024, 2035	71.334
4	NE-1GJ04	Alternative 1	2019, 2025, 2029, 2032, 2035, 2037	18.14
		Alternative 2	2019, 2025, 2030, 2035, 2038	33.06
		Alternative 3	2023, 2034	77.454
5	NH-14GJ05	Alternative 1	2019, 2023, 2027, 2031, 2035	1.683
		Alternative 2	2019, 2023, 2028, 2032, 2035	7.012
		Alternative 3	2022, 2033	33.714
6	NH-2UP01	Alternative 1	2019, 2023, 2027, 2031, 2035	7.941
		Alternative 2	2019, 2023, 2027, 2031, 2035, 2038	11.633
		Alternative 3	2023, 2033	37.271
7	NH-2UP02	Alternative 1	2019, 2023, 2027, 2031, 2035	3.504
		Alternative 2	2019, 2021, 2025, 2029, 2030, 2033, 2037	4.07
		Alternative 3	2024, 2034	41.309
		Alternative 1	2020, 2024, 2028, 2032, 2036	5.85

8	NH-37AS01	Alternative 2	2020, 2024, 2026, 2030, 2034, 2036	8.98
0		Alternative 3	2025, 2035	28.92
	NH-4KA01	Alternative 1	2019, 2021, 2023, 2025-2031	54.55
9		Alternative 2	2019, 2022, 2023, 2026, 2028, 2030-2038	36.45
		Alternative 3	2022, 2030, 2037	9.88
	NH-4KA02	Alternative 1	2019, 2023, 2027, 2031, 2035	16.849
10		Alternative 2	2019, 2024, 2028, 2029, 2034, 2038	23.3
		Alternative 3	2024, 2036	33.77
	NH-4KA03	Alternative 1	2019, 2023, 2026, 2028, 2030, 2032, 2034-2038	19.41
11		Alternative 2	2019, 2022, 2026, 2029, 2032, 2034, 2035, 2037	71.63
		Alternative 3	2022, 2032	129.1
	NH-5AP01	Alternative 1	2019, 2023, 2027, 2031, 2035, 2038	9.436
12		Alternative 2	2020, 2024, 2026, 2030, 2034, 2037	14.41
		Alternative 3		49
	NH-5AP02	Alternative 1	2020, 2024, 2028, 2032, 2038	0.107
13		Alternative 2	2020, 2021, 2025, 2029, 2031, 2035	9.28
		Alternative 3	2025, 2036	48.39
	NH-5AP03	Alternative 1	2019, 2023, 2027, 2031, 2035, 2038	19.87
14		Alternative 2	2019, 2022, 2026, 2027, 2030, 2034, 2036	13.55
		Alternative 3	2022, 2032	37
	NH-5AP04	Alternative 1	2019, 2023, 2027, 2031, 2035, 2038	19.87
15		Alternative 2	2019, 2022, 2026, 2027, 2030, 2034, 2036	13.55
		Alternative 3	2022, 2032	37
	NH-4MH01	Alternative 1	2020, 2024, 2028, 2032, 2036	37.528
16		Alternative 2	2019, 2022, 2027, 2030, 2034, 2036	27
		Alternative 3	2025, 2035	20.95
	NH-7MH02	Alternative 1	2020, 204, 2028, 2032	5.409
17		Alternative 2	2020, 2024, 2026, 2031, 2035, 2037	8.436
		Alternative 3	2035, 2038	21.193
	NH-7MH03	Alternative 1	2019, 2024, 2029, 2033, 2037	21.464
18		Alternative 2	2019, 2025, 2032, 2038	19.621

		Alternative 3	2025, 2038	24.532
19	NH-73 01	Alternative 1	2019, 2023, 2027, 2030, 2033, 2035, 2037	16.22
		Alternative 2	2019, 2022, 2026, 2029, 2032, 2034, 2037	61.521
		Alternative 3	2023, 2032	62.32
20	NH-73 02	Alternative 1	2019, 2023, 2027, 2030, 2033, 2035, 2037	16.047
		Alternative 2	2019, 2023, 2024, 2027, 2031, 2034, 2037, 2038	41.385
		Alternative 3	2023, 2032	49.49
21	NH-73 03	Alternative 1	2019, 2023, 2027, 2030, 2033, 2035, 2037	171.75
		Alternative 2	2019, 2023, 2027, 2031, 2034, 2037	272.99
		Alternative 3	2021, 2030	285.23
22	NH-73 04	Alternative 1	2019, 2023, 2027, 2033, 2035, 2037	256.237
		Alternative 2	2019, 2023, 2027, 2031, 2034, 2037	427.39
		Alternative 3	2022, 2031	261.371
23	NH-74 01	Alternative 1	2019, 2023, 2027, 2031, 2035, 2038	193.766
		Alternative 2	2019, 2020, 2023, 2026, 2029, 2033, 2036	118.625
		Alternative 3	2022, 2032	227.967
24	NH-74 02	Alternative 1	2019, 2023, 2027, 2031, 2035, 2038	245.779
		Alternative 2	2019, 2020, 2023, 2025, 2031, 2034, 2038	174.765
		Alternative 3	2022, 2032	259.478
25	NH-72 01	Alternative 1	2019, 2023, 2027, 2031, 2035	233.02
		Alternative 2	2019-2021, 2025, 2027, 2031, 2035, 2037	229.872
		Alternative 3	2022, 2033	128.71
26	NH-72 02	Alternative 1	2019, 2023, 2027, 2031, 2035, 2038	90.86
		Alternative 2	2019, 2020, 2023, 2027, 2028, 2031, 2035, 2038	182.241
		Alternative 3	2023, 2033	208.849
27	NH-72 03	Alternative 1	2019, 2023, 2027, 2031, 2035, 2038	176.749
		Alternative 2	2019-2021, 2024, 2028, 2031, 2035, 2037	304.448
		Alternative 3	2022, 2032	255.131

	NH-72 04	Alternative 1	2019, 2023, 2027, 2030, 2033, 2035, 2037	274.12
28		Alternative 2	2019, 2020, 2023, 2025, 2028, 2032, 2035, 2038	204.178
		Alternative 3	2022, 2031	404.348
	NH-72 05	Alternative 1	2019, 2023, 2027, 2031, 2034, 2036, 2038	288.577
29		Alternative 2	2019, 2023, 2027, 2031, 2034, 2037	266.65
		Alternative 3	2022, 2031	514.884

Priority ranking model which includes the order in which the optimum M&R strategy will be assigned to road sections has been established on the basis of NPV/CAP ratio.

Table 6. 4 Prioritization of Road Sections

Sections	Ranking Order
NH-72 05	1
NH-72 04	2
NH-73 03	3
NH-73 04	4
NH-74 02	5
NH-72 03	6
NH-74 01	7
NH-72 02	8
NH-72 01	9
NH-4KA03	10
NE-1GJ02	11
NE-1GJ04	12
NE-1GJ01	13
NE-1GJ03	14
NH-73 01	15
NH-73 02	16
NH-5AP01	17
NH-5AP02	18
NH-2UP02	19
NH-5AP03	20
NH-5AP04	21
NH-2UP01	22
NH-4KA02	23
NH-14GJ05	24
NH-37AS01	25
NH-7MH03	26
NH-7MH02	27
NH-4MH01	28
NH-4KA01	29

CHAPTER-7

CONCLUSIONS

7.1 MAJOR DISCOVERIES

The scientific investigations carried out in this research study has drawn certain noticeable findings which have been stated as follows:

- (i) It has been concluded that a scientific approach system should be adopted before planning road maintenance strategy for providing long lasting management and investment solutions to concerned road agencies.
- (ii) HDM tool used in the study has developed a distress prediction model for all the identified flexible pavement sections of NH network for an analysis period of 20 years. The maintenance strategies assigned to the road network has been traced out from graphical representations and results show that the alternatives intervene precisely as per the defined critical limits of control parameters i.e., roughness and total damaged area. Pavement performance in terms of distress patterns and rate of deterioration is a function of the physical characteristics of road such as structural condition, traffic loading, pavement age, climatic conditions etc. and previous maintenance work records.
- (iii) Remaining service life of all the road sections has been estimated to determine the capacity of pavement sections to cater the projected traffic loads and safeguard against climatic conditions in the absence of any routine and/or periodic maintenance work. RSL has been defined from the year of last maintenance activity and/or rehabilitation work done till the intervention of reconstruction of road pavements. Residual life of candidate road sections w.r.t the year when any rehabilitation and/or resurfacing work was done: for NH-73 03, NH-72 (km 115-118, 180-197), NH-73 (km 25-47) road section is 10 years, for NH-14GJ 05, NH-72 (km 132-148) road section is 11 years, for NH-4KA 01, NH-4KA 03, NH-5AP 03, NH-5AP 04, NH-74, NH-73 01, NH-73 02 road sections is 12 years, for NE-1GJ 04, NH-2UP 01, NH-2UP 02, NH-72 (km 118-132), NH-72A (km 0-25), NH-74 (km 0-30) road sections is 13 years, for NE-12UP, for NE-1GJ 01, NE-1GJ 02, NE-1GJ 03, NH-4KA 02, NH-5AP 01 road sections is 14 years, for NH-4MH, NH-5AP 02, NH-7MH 03, NH-7MH 02 road

sections is 15 years. RSL varies from 10-15 years for various road sections which indicates that the identified road sections require maintenance.

- (iv) Genetic programming system has been tailored to generate distress prediction models which defines the quantitative assessment of future pavement performance. Statistical evaluation results prove that GP prediction models are highly accurate and applicable for National highway roads having flexible pavements and high traffic loading conditions. Validation of GP model has been done in terms of fitness measures such as R^2 and RMSE. R^2 obtained from graphs are of the values 0.85, 0.75, 0.93 and 0.97 for cracking, ravelling, rutting, Roughness models respectively which indicate high adequacy of these models.
- (v) Comparison of predicted roughness values obtained from HDM-4 and GP models with the observed field values for all road sections has been done to check the functional capabilities and adequacy of the models. Variations in roughness values predicted by HDM model for all road sections vary in the range of 1.47% to 2.8% whereas for GP model the variability range lies from 1.41% to 3.1% which is very much acceptable.
- (vi) Economic analysis has been performed to predict the most appropriate maintenance strategy in terms of economical range applicable for NH network. Maintenance plan corresponding to all the proposed work alternatives assigned to each road section has been laid out and based upon maximum NPV/COST ratio, optimum maintenance solution for all the road sections has been identified which comes out to be Alternative 3 i.e., 'Major Overlay'.

7.2 SUGGESTIONS

- (i) Extensive study can be conducted on long term pavement performance of rigid pavements to develop a scientific road management strategy using HDM-4.
- (ii) Genetic algorithm based prediction models can be developed to predict pavement deterioration for rigid pavements.
- (iii) Integration of road appraisal systems with GIS techniques for efficient road management solutions.

REFERENCES

- Chandra, S., Sekhar, C. R., Bharti, A. K., & Kangadurai, B. (2012). Relationship between pavement roughness and distress parameters for Indian highways. *Journal of Transportation Engineering*, 139(5), 467-475.
- Chopra, T., Parida, M., Kwatra, N., & Chopra, P. (2018). Development of Pavement Distress Deterioration Prediction Models for Urban Road Network Using Genetic Programming. *Advances in Civil Engineering*, 2018.
- Chopra, T., Parida, M., Kwatra, N., & Mandhani, J. (2017). Development of Pavement Maintenance Management System (PMMS) of urban road network using HDM-4 model. *International Journal of Engineering and Applied Sciences*, 9(1), 14-31.
- Deori, S., Choudhary, R., Tiwari, D., & Gangopadhyay, S. (2018). Calibration of HDM-4 models for Indian conditions of flexible pavement having modified bitumen in wearing course. *International Journal of Pavement Engineering*, 19(9), 772-785.
- Girimath, S. B., and Fellow, P. (2014). Pavement Management System for Urban Roads. *International Journal of Scientific and Developmeny*, 2(3), 282-284.
- Gupta, A., Kumar, P., & Rastogi, R. (2011). Pavement deterioration and maintenance model for low volume roads. *International Journal of Pavement Research and Technology*, 4(4), 195-202.
- Jain, K., Jain, S. S., & Chauhan, M. S. (2013). Selection of optimum maintenance and rehabilitation strategy for multilane highways. *International Journal for Traffic and Transport Engineering*, 3(3), 269-278.
- Jain, S. S., Parida, M., & Aggarwal, S. (2004). Application of HDM-4 for network level pavement management system for Indian National Highway network.!. *CE & CR*, 46-55.
- Jelokhani-Niaraki, M. R., Alesheikh, A. A., Alimohammadi, A., Sadeghi-Niaraki, A., & Kim, K. (2011). An approach for automatic updating of GIS road segments for a pavement management system (PMS). *Journal of Spatial Science*, 56(2), 253-267.

- Jorge, D., & Ferreira, A. (2012). Road network pavement maintenance optimisation using the HDM-4 pavement performance prediction models. *International Journal of Pavement Engineering*, 13(1), 39-51.
- Khan, M. U., & Odoki, J. B. (2010). Establishing optimal pavement maintenance standards using the HDM-4 Model for Bangladesh. *Journal of Civil Engineering (IEB)*, 38(1), 1-16.
- Mandhani, J., & Chopra, T. G. (2016). *Development of Pavement Maintenance Management System (PMMS) of Patiala City Road Network Using HDM-4 Model* (Doctoral dissertation).
- Mathew, B. S., & Isaac, K. P. (2014). Optimisation of maintenance strategy for rural road network using genetic algorithm. *International Journal of Pavement Engineering*, 15(4), 352-360.
- Msallam, M., Al Rawi, O. S., Abudayyeh, D., & Assi, I. (2014). Development of a Pavement Management System to be Used in Highway Pavement Evaluation in Jordan. *Development*, 6(9).
- Odoki, J. B., & Kerali, H. G. (2000). Analytical framework and model descriptions. *The Highway Development and Management Series*, 4.
- Sandra, A. K., & Sarkar, A. K. (2013). Development of a model for estimating International Roughness Index from pavement distresses. *International Journal of Pavement Engineering*, 14(8), 715-724.
- Shah, Y. U., Jain, S. S., Tiwari, D., & Jain, M. K. (2013). Development of overall pavement condition index for urban road network. *Procedia-Social and Behavioral Sciences*, 104, 332-341.
- Shah, Y. U., Jain, S. S., Tiwari, D., & Jain, M. K. (2013). Modeling the pavement serviceability index for urban roads in Noida. *International Journal of Pavement Research and Technology*, 6(1), 66-72.
- Surendrakumar, K., Prashant, N., & Mayuresh, P. (2013). Application of Markovian probabilistic process to develop a decision support system for pavement maintenance management. *International Journal of Scientific & Technology Research*, 2(8), 295-303.

Thube, D. T. (2013). Highway Development and Management Model (HDM-4): calibration and adoption for low-volume roads in local conditions. *International Journal of Pavement Engineering*, 14(1), 50-59.

ANNEXURE

ANNEXURE A

A.1 Average Roughness values predicted using HDM-4 model against all the four maintenance alternatives assigned to the NH road sections.

Table A.1.1: Roughness progression for work Alternative 1 (Resealing)

Roughness Progression: Alternative 1															
Year	Sections														
	NE-1GJ01	NE-1GJ02	NE-1GJ03	NE-1GJ04	NE-14GJ05	NH-2UP01	NH-2UP02	NH-37AS01	NH-4KA01	NH-4KA02	NH-4KA03	NH-4MH01	NH-4MH02	NH-4MH03	NH-5AP01
2019	2.47	2.54	2.55	2.55	2.79	2.6	2.88	2.57	3.43	3.8	3.82	3.1	2.57	2.48	2.57
2020	2.51	2.57	2.59	2.59	2.84	2.65	2.95	2.66	3.61	3.86	3.91	3.23	2.65	2.56	2.63
2021	2.56	2.61	2.62	2.62	2.89	2.7	3.01	2.71	3.79	3.93	4	3.32	2.71	2.63	2.68
2022	2.6	2.64	2.66	2.66	2.94	2.75	3.08	2.77	3.96	3.99	4.09	3.41	2.77	2.71	2.74
2023	2.67	2.67	2.7	2.7	3.01	2.83	3.18	2.84	4.14	4.08	4.21	3.51	2.83	2.8	2.82
2024	2.72	2.7	2.76	2.74	3.06	2.89	3.25	2.92	4.3	4.15	4.3	3.63	2.92	2.94	2.88
2025	2.76	2.74	2.8	2.78	3.12	2.94	3.32	2.98	4.45	4.22	4.39	3.73	2.98	3.02	2.94
2026	2.81	2.77	2.84	2.82	3.17	3	3.39	3.05	4.59	4.29	4.49	3.82	3.04	3.1	3
2027	2.88	2.8	2.88	2.86	3.25	3.08	3.49	3.11	4.72	4.38	4.58	3.93	3.1	3.18	3.08
2028	2.93	2.84	2.92	2.9	3.31	3.14	3.57	3.2	4.81	4.45	4.68	4.06	3.19	3.29	3.14
2029	2.98	2.87	2.96	2.94	3.36	3.2	3.64	3.27	4.87	4.52	4.75	4.16	3.25	3.44	3.21
2030	3.03	2.91	3.01	2.98	3.42	3.26	3.72	3.34	4.9	4.59	4.84	4.26	3.32	3.53	3.27

2031	3.1	2.94	3.05	3.02	3.5	3.34	3.83	3.41	4.92	4.69	4.86	4.37	3.38	3.62	3.36
2032	3.15	2.98	3.09	3.06	3.56	3.4	3.9	3.5	4.93	4.73	4.95	4.5	3.47	3.71	3.42
2033	3.2	3.01	3.13	3.1	3.62	3.47	3.98	3.57	4.93	4.81	4.94	4.61	3.54	3.83	3.49
2034	3.11	3.05	3.18	3.15	3.68	3.53	4.07	3.64	4.92	4.89	5.03	4.72	3.61	3.93	3.56
2035	3.26	3.09	3.22	3.19	3.76	3.62	4.18	3.72	4.92	4.99	4.99	4.83	3.68	4.02	3.65
2036	3.41	3.12	3.27	3.23	3.83	3.68	4.26	3.82	4.91	4.95	4.96	4.98	3.77	4.12	3.72
2037	3.56	3.16	3.31	3.28	3.89	3.75	4.35	3.89	4.9	5.02	4.93	4.98	3.84	4.25	3.79
2038	3.72	3.2	3.36	3.32	3.96	3.82	4.44	3.97	4.88	5.1	4.91	5.09	3.91	4.35	3.86
		Sections													
Year	NH-5AP02	NH-5AP03	NH-5AP04	NH-73 01	NH-73 02	NH-73 03	NH-73 04	NH-74 01	NH-74 02	NH-72 01	NH-72 02	NH-72 03	NH-72 04	NH-72 05	
2019	2.88	3.05	3.05	3.73	2.53	7.22	6.56	4.69	4.92	6.06	5.26	5.89	5.43	6.49	
2020	2.98	3.13	3.13	3.81	2.63	6.64	6.15	4.79	4.99	5.72	5.16	5.61	5.33	6.07	
2021	3.05	3.21	3.21	3.91	2.74	6.85	6.33	4.93	5.16	5.83	5.26	5.73	5.49	6.22	
2022	3.12	3.3	3.3	4	2.85	7.07	6.52	5.07	5.34	5.94	5.36	5.84	5.65	6.38	
2023	3.19	3.41	3.41	4.12	3	7.33	6.75	5.24	5.55	6.08	5.49	5.99	5.84	6.6	
2024	3.28	3.5	3.5	4.22	3.11	6.71	6.28	5.18	5.43	5.74	5.33	5.68	5.62	6.15	
2025	3.35	3.58	3.58	4.31	3.22	6.92	6.47	5.33	5.61	5.84	5.43	5.8	5.79	6.3	
2026	3.43	3.68	3.68	4.41	3.34	7.15	6.66	5.47	5.79	5.95	5.54	5.92	5.95	6.46	
2027	3.5	3.79	3.79	4.54	3.49	7.4	6.88	5.65	6	6.09	5.67	6.07	6.15	6.68	
2028	3.6	3.88	3.88	4.64	3.6	6.76	6.38	5.47	5.75	5.75	5.45	5.74	5.84	6.2	

2029	3.67	3.98	3.98	4.74	3.73	6.98	6.56	5.62	5.93	5.86	5.56	5.86	6.01	6.36
2030	3.75	4.07	4.07	4.85	3.85	7.2	6.76	5.77	6.11	5.97	5.66	5.98	6.18	6.52
2031	3.83	4.2	4.2	4.88	3.97	6.62	6.29	5.95	6.33	6.1	5.8	6.13	5.86	6.74
2032	3.93	4.29	4.29	4.98	4.09	6.82	6.47	5.68	5.98	5.76	5.54	5.79	6.02	6.25
2033	4.01	4.39	4.39	5.09	4.22	7.04	6.66	5.83	6.16	5.87	5.65	5.91	6.19	6.4
2034	4.09	4.5	4.5	5.05	4.34	6.5	6.21	5.98	6.35	5.98	5.77	6.03	5.86	6.57
2035	4.17	4.63	4.63	5.15	4.47	6.7	6.39	6.17	6.57	6.12	5.9	6.18	6.02	6.12
2036	4.25	4.72	4.72	5.09	4.59	6.25	6.01	5.84	6.15	5.77	5.62	5.83	5.74	6.28
2037	4.34	4.83	4.83	5.19	4.71	6.43	6.18	5.99	6.34	5.88	5.73	5.95	5.89	5.91
2038	4.42	4.94	4.94	5.12	4.8	6.05	5.86	6.15	6.53	5.99	5.85	6.08	5.64	6.06

Table A.1.2: Roughness progression for work Alternative 2 (Resealing + Overlay)

Roughness Progression: Alternative 2															
Year	Sections														
	NE-1GJ01	NE-1GJ02	NE-1GJ03	NE-1GJ04	NE-14GJ05	NH-2UP01	NH-2UP02	NH-37AS01	NH-4KA01	NH-4KA02	NH-4KA03	NH-4MH01	NH-4MH02	NH-4MH03	NH-5AP01
2019	2.47	2.54	2.55	2.55	2.79	2.6	2.88	2.57	3.43	3.8	3.82	3.1	2.57	2.48	2.57
2020	2.51	2.57	2.59	2.59	2.84	2.65	2.95	2.66	2.35	2.3	2.32	3.23	2.65	2.56	2.63
2021	2.56	2.61	2.62	2.62	2.89	2.7	3.01	2.71	2.51	2.34	2.39	2.26	2.71	2.63	2.68
2022	2.6	2.64	2.66	2.66	2.94	2.75	3.08	2.77	2.64	2.39	2.47	2.34	2.77	2.71	2.74
2023	2.67	2.67	2.7	2.7	3.01	2.83	3.18	2.84	2.78	2.44	2.54	2.44	2.83	2.8	2.82
2024	2.72	2.7	2.76	2.74	2.21	2.89	2.24	2.92	2.91	2.51	2.6	2.51	2.92	2.94	2.88
2025	2.76	2.74	2.8	2.78	2.25	2.94	2.3	2.98	3.04	2.56	2.67	2.58	2.98	3.02	2.94
2026	2.81	2.77	2.84	2.82	2.3	3	2.38	3.05	2.28	2.61	2.74	2.66	3.04	3.1	3
2027	2.88	2.8	2.88	2.86	2.36	3.08	2.43	3.11	2.4	2.66	2.81	2.76	3.1	3.18	3.08
2028	2.93	2.84	2.92	2.9	2.4	2.22	2.49	3.2	2.5	2.73	2.88	2.83	3.19	3.29	2.23
2029	2.98	2.87	2.96	2.94	2.44	2.27	2.55	2.24	2.59	2.78	2.94	2.91	2.24	3.44	2.27
2030	3.03	2.91	3.01	2.98	2.49	2.33	2.63	2.3	2.68	2.83	3.01	2.99	2.29	2.28	2.33
2031	3.1	2.94	3.05	3.02	2.56	2.37	2.69	2.36	2.77	2.89	2.23	3.1	2.34	2.35	2.4
2032	2.22	2.98	2.21	2.21	2.6	2.42	2.75	2.41	2.85	2.96	2.29	2.24	2.41	2.42	2.45
2033	2.26	3.01	2.24	2.24	2.65	2.47	2.81	2.47	2.93	3.02	2.34	2.32	2.46	2.5	2.5
2034	2.31	3.05	2.27	2.27	2.69	2.54	2.9	2.52	3	3.07	2.39	2.4	2.51	2.59	2.55
2035	2.34	2.2	2.31	2.3	2.77	2.59	2.96	2.6	3.07	3.13	2.44	2.46	2.56	2.69	2.63
2036	2.38	2.23	2.35	2.34	2.81	2.64	3.02	2.65	2.23	3.21	2.5	2.53	2.64	2.76	2.68
2037	2.42	2.26	2.38	2.37	2.86	2.69	3.09	2.71	2.28	2.23	2.54	2.6	2.69	2.84	2.73
2038	2.46	2.29	2.41	2.4	2.91	2.76	3.18	2.77	2.33	2.28	2.59	2.69	2.74	2.92	2.79

Year	Sections													
	NH-5AP02	NH-5AP03	NH-5AP04	NH-7301	NH-7302	NH-7303	NH-7304	NH-7401	NH-7402	NH-7201	NH-7202	NH-7203	NH-7204	NH-7205
2019	2.88	3.05	3.05	3.73	2.53	7.22	6.56	4.69	4.92	6.06	5.26	5.89	5.43	6.49
2020	2.98	2.24	2.24	2.31	2.63	4.51	4	2.56	2.76	3.57	2.97	3.45	3.13	3.94
2021	3.05	2.31	2.31	2.39	2.74	4.68	4.15	2.67	2.9	3.66	3.04	3.54	3.26	4.09
2022	3.12	2.4	2.4	2.47	2.85	4.88	4.32	2.79	3.05	3.75	3.14	3.64	3.4	4.26
2023	3.19	2.46	2.46	2.54	3	2.73	2.41	2.88	2.28	2.3	2.24	2.3	2.3	2.4
2024	3.28	2.53	2.53	2.61	3.11	2.86	2.52	2.98	2.39	2.37	2.31	2.37	2.4	2.53
2025	2.25	2.6	2.6	2.68	3.22	3.01	2.65	3.09	2.51	2.44	2.39	2.46	2.52	2.68
2026	2.31	2.7	2.7	2.78	3.34	2.27	2.76	3.22	2.61	2.5	2.44	2.52	2.61	2.79
2027	2.37	2.76	2.76	2.86	3.49	2.39	2.87	2.27	2.72	2.56	2.5	2.59	2.71	2.89
2028	2.43	2.84	2.84	2.93	2.31	2.51	2.98	2.36	2.83	2.62	2.57	2.66	2.81	3.01
2029	2.48	2.91	2.91	3.01	2.4	2.62	3.12	2.47	2.97	2.71	2.65	2.75	2.94	3.18
2030	2.54	3.01	3.01	2.23	2.52	2.72	2.27	2.55	3.07	2.77	2.72	2.82	3.04	2.28
2031	2.62	2.23	2.23	2.3	2.6	2.84	2.37	2.63	3.18	2.83	2.78	2.89	3.14	2.4
2032	2.68	2.3	2.3	2.38	2.7	2.94	2.49	2.72	3.3	2.9	2.85	2.97	3.25	2.54
2033	2.74	2.38	2.38	2.44	2.79	3.05	2.58	2.84	3.44	2.99	2.94	3.07	2.28	2.64
2034	2.8	2.44	2.44	2.51	2.88	3.16	2.68	2.92	2.3	3.05	3	2.24	2.36	2.73
2035	2.88	2.5	2.5	2.57	2.98	2.27	2.77	3.01	2.4	3.12	3.07	2.3	2.47	2.84
2036	2.94	2.56	2.56	2.63	3.06	2.37	2.86	3.11	2.51	3.19	3.14	2.38	2.55	2.93
2037	3	2.63	2.63	2.69	3.16	2.45	2.95	2.25	2.6	3.29	2.24	2.44	2.63	3.03
2038	3.07	2.69	2.69	2.76	2.26	2.54	3.04	2.33	2.69	2.25	2.3	2.5	2.71	2.26

Table A.1.3: Roughness progression for work Alternative 3 (Major Overlay)

Roughness Progression: Alternative 3															
Year	Sections														
	NE-1GJ01	NE-1GJ02	NE-1GJ03	NE-1GJ04	NE-14GJ05	NH-2UP01	NH-2UP02	NH-37AS01	NH-4KA01	NH-4KA02	NH-4KA03	NH-4MH01	NH-4MH02	NH-4MH03	NH-5AP01
2019	2.47	2.54	2.55	2.55	2.79	2.6	2.88	2.57	3.43	3.8	3.82	3.1	2.57	2.48	2.57
2020	2.59	2.62	2.63	2.64	3.23	2.74	3	2.66	3.73	3.88	4.33	3.23	2.65	2.58	2.67
2021	2.88	2.86	2.76	2.93	6.37	3.03	3.22	2.79	4.78	4.11	6.16	3.4	2.79	2.79	2.81
2022	3.18	4.99	3.32	4.54	2.29	4.6	4.06	3.01	14.46	4.76	2.32	3.67	3	3.31	3.01
2023	5.34	16	5.75	16	2.38	13.23	7.94	3.12	2.5	7.74	2.45	3.84	3.11	4.24	3.99
2024	15.42	2.3	16	2.3	2.48	2.31	2.31	4.15	2.79	2.27	2.59	5.99	3.78	5.83	12.1
2025	2.3	2.41	2.3	2.41	2.61	2.43	2.44	12.81	3.11	2.34	2.76	16	8.47	10.13	2.29
2026	2.42	2.53	2.41	2.53	2.75	2.57	2.58	2.31	3.49	2.43	2.96	2.33	2.26	2.26	2.38
2027	2.54	2.67	2.54	2.67	2.92	2.73	2.74	2.43	3.92	2.52	3.19	2.46	2.34	2.34	2.49
2028	2.69	2.84	2.69	2.83	3.13	2.92	2.93	2.57	4.45	2.64	3.47	2.61	2.41	2.41	2.61
2029	2.86	3.03	2.86	3.03	3.37	3.14	3.16	2.73	5.89	2.77	4.03	2.79	2.51	2.51	2.76
2030	3.06	3.26	3.06	3.26	3.83	3.41	3.44	2.91	12.48	2.93	5.57	3	2.62	2.62	2.93
2031	3.3	3.54	3.3	3.53	4.89	3.95	3.99	3.13	2.6	3.12	9.22	3.24	2.74	2.74	3.13
2032	3.59	4.07	3.58	4.06	7.07	5.34	5.46	3.4	2.99	3.35	2.38	3.54	2.9	2.9	3.38
2033	4.14	5.41	4.13	5.38	2.33	8.54	8.86	3.92	3.43	3.72	2.55	4.2	3.08	3.08	3.83
2034	5.56	8.32	5.53	8.25	2.46	2.36	2.37	5.28	3.92	4.5	2.74	6.1	3.29	3.29	4.92
2035	8.7	2.35	8.62	2.35	2.61	2.53	2.53	8.39	4.48	5.98	2.96	2.38	3.64	3.64	7.19
2036	2.36	2.5	2.36	2.5	2.79	2.72	2.73	2.36	5.46	8.61	3.23	2.55	4.35	4.35	2.33
2037	2.51	2.67	2.51	2.67	3	2.94	2.95	2.52	10.84	2.31	3.54	2.76	5.68	5.68	2.47
2038	2.69	2.87	2.69	2.86	3.25	3.19	3.21	2.71	2.62	2.42	3.93	2.99	8.01	8.01	2.62

Year	Sections													
	NH-5AP 02	NH-5AP03	NH-5AP04	NH-73 01	NH-73 02	NH-73 03	NH-73 04	NH-74 01	NH-74 02	NH-72 01	NH-72 02	NH-72 03	NH-72 04	NH-72 05
2019	2.88	3.05	3.05	3.73	2.53	7.22	6.56	4.69	4.92	6.06	5.26	5.89	5.43	6.49
2020	2.98	3.4	3.4	3.91	2.69	2.34	2.34	4.9	5.15	2.28	5.51	6.17	5.9	2.33
2021	3.14	4.18	4.18	4.63	3.09	2.49	2.49	5.54	5.82	2.36	5.71	2.32	7.12	2.47
2022	3.36	11.82	11.82	7.93	6.2	2.66	2.66	10.1	8.63	2.46	7.79	2.45	2.35	2.62
2023	3.47	2.33	2.33	2.36	2.36	2.85	2.85	2.32	2.32	2.58	2.33	2.59	2.5	2.8
2024	4.52	2.46	2.46	2.53	2.53	3.08	3.08	2.45	2.45	2.71	2.46	2.76	2.67	3.01
2025	13.43	2.61	2.61	2.72	2.71	3.35	3.35	2.6	2.6	2.87	2.61	2.97	2.87	3.27
2026	2.29	2.78	2.78	2.94	2.93	3.85	3.85	2.77	2.77	3.06	2.79	3.2	3.11	3.72
2027	2.39	2.99	2.99	3.19	3.18	5.18	5.17	2.97	2.98	3.29	2.99	3.49	3.39	4.86
2028	2.5	3.24	3.24	3.5	3.49	8.52	8.5	3.21	3.22	3.68	3.24	4.08	3.73	7.61
2029	2.62	3.53	3.53	3.87	3.86	2.4	2.4	3.51	3.51	4.55	3.54	5.69	4.53	2.38
2030	2.77	4.18	4.18	4.79	4.76	2.6	2.6	4.12	4.13	6.29	4.19	9.44	7.04	2.56
2031	2.95	6.01	6.01	7.78	7.71	2.82	2.82	5.81	5.85	2.31	6.04	2.37	2.41	2.77
2032	3.16	2.37	2.37	2.43	2.42	3.08	3.08	9.8	9.91	2.44	2.38	2.55	2.61	3.01
2033	3.41	2.55	2.55	2.65	2.64	3.39	3.39	2.38	2.38	2.58	2.55	2.75	2.84	3.29
2034	3.88	2.75	2.75	2.9	2.89	3.75	3.75	2.55	2.55	2.75	2.75	2.98	3.11	3.63
2035	5.03	2.98	2.98	3.19	3.18	4.2	4.19	2.75	2.76	2.94	2.99	3.24	3.42	4.04
2036	7.47	3.25	3.25	3.53	3.52	5.38	5.37	2.99	2.99	3.17	3.26	3.57	3.79	5.1
2037	2.34	3.58	3.58	3.93	3.92	9.78	9.76	3.26	3.27	3.45	3.58	3.96	4.25	8.82
2038	2.47	3.98	3.98	4.9	4.87	2.47	2.47	3.59	3.59	4.02	3.98	4.95	5.48	2.45

Table A.1.4: Roughness progression for work Alternative 4 (Routine Maintenance)

Roughness Progression: Base Alternative															
Year	Sections														
	NE-1GJ01	NE-1GJ02	NE-1GJ03	NE-1GJ04	NE-14GJ05	NH-2UP01	NH-2UP02	NH-37AS01	NH-4KA01	NH-4KA02	NH-4KA03	NH-4MH01	NH-4MH02	NH-4MH03	NH-5AP01
2019	2.47	2.54	2.55	2.55	2.79	2.6	2.88	2.57	3.43	3.8	3.82	3.1	2.57	2.48	2.57
2020	2.59	2.62	2.63	2.64	3.18	2.64	3	2.66	3.73	3.88	4.23	3.23	2.65	2.58	2.67
2021	2.85	2.87	2.77	2.86	3.47	2.86	3.22	2.79	4.76	4.02	4.47	3.4	2.79	2.79	2.71
2022	2.82	3.2	2.96	3.25	3.77	3.05	3.46	2.97	4.83	4.2	4.46	3.63	2.97	3.01	2.82
2023	2.86	3.05	2.91	3.11	4.08	3.04	3.49	3.08	5.19	4.39	4.57	3.79	3.06	3.21	3
2024	2.9	3.07	2.94	3.14	4	3.11	3.6	3.16	5.57	4.49	4.69	3.93	3.14	3.42	3.09
2025	2.94	3.09	2.96	3.16	4.06	3.18	3.72	3.24	5.98	4.51	4.82	4.08	3.21	3.67	3.16
2026	2.98	3.11	2.99	3.19	4.12	3.25	3.84	3.33	6.41	4.59	4.95	4.24	3.29	3.93	3.24
2027	3.02	3.12	3.01	3.22	4.18	3.33	3.97	3.42	6.86	4.67	5.08	4.4	3.38	4.17	3.32
2028	3.06	3.14	3.04	3.24	4.25	3.41	4.11	3.52	7.34	4.76	5.22	4.58	3.47	4.35	3.41
2029	3.11	3.16	3.07	3.27	4.32	3.5	4.25	3.63	7.85	4.85	5.38	4.76	3.56	4.54	3.5
2030	3.16	3.18	3.1	3.3	4.39	3.59	4.4	3.73	8.39	4.94	5.54	4.96	3.66	4.73	3.59
2031	3.21	3.2	3.13	3.33	4.47	3.68	4.56	3.85	8.96	5.04	5.71	5.16	3.76	4.92	3.69
2032	3.26	3.21	3.16	3.36	4.55	3.78	4.73	3.97	9.57	5.14	5.88	5.38	3.86	5.1	3.79
2033	3.32	3.24	3.19	3.39	4.63	3.88	4.91	4.09	10.21	5.24	6.07	5.6	3.98	5.29	3.9
2034	3.38	3.26	3.23	3.43	4.71	3.99	5.09	4.23	10.86	5.35	6.26	5.84	4.09	5.49	4.01
2035	3.44	3.29	3.27	3.47	4.8	4.1	5.28	4.37	11.53	5.46	6.47	6.09	4.22	5.69	4.13
2036	3.5	3.31	3.31	3.51	4.89	4.22	5.49	4.51	12.2	5.58	6.68	6.35	4.35	5.9	4.25
2037	3.57	3.33	3.35	3.55	4.99	4.35	5.7	4.67	12.89	5.7	6.91	6.63	4.48	6.12	4.38
2038	3.64	3.36	3.39	3.59	5.08	4.48	5.92	4.83	13.58	5.83	7.15	6.92	4.63	6.35	4.52

Year	Sections													
	NH-5AP02	NH-5AP03	NH-5AP04	NH-7301	NH-7302	NH-7303	NH-7304	NH-7401	NH-7402	NH-7201	NH-7202	NH-7203	NH-7204	NH-7205
2019	2.88	3.05	3.05	3.73	2.53	7.22	6.56	4.69	4.92	6.06	5.26	5.89	5.43	6.49
2020	2.98	3.33	3.33	3.9	2.69	7.78	6.85	4.89	5.14	6.27	5.44	6.17	5.9	6.83
2021	3.14	3.42	3.42	4.52	3.09	8.02	7.4	5.41	5.61	6.64	5.77	2.32	7.12	7.5
2022	3.34	3.53	3.53	4.46	3.62	8.38	7.58	5.51	6.1	6.91	5.81	2.45	2.35	7.75
2023	3.43	3.66	3.66	4.59	3.62	8.77	7.91	5.74	6.59	6.94	5.94	2.59	2.5	8.03
2024	3.52	3.78	3.78	4.73	3.83	9.17	8.25	5.99	6.96	7.09	6.09	2.76	2.67	8.31
2025	3.61	3.92	3.92	4.87	4.04	9.6	8.61	6.25	7.22	7.25	6.23	2.97	2.87	8.61
2026	3.71	4.06	4.06	5.03	4.27	10.05	8.99	6.52	7.61	7.41	6.39	3.2	3.11	8.92
2027	3.81	4.21	4.21	5.18	4.51	10.51	9.39	6.81	8.02	7.58	6.55	3.49	3.39	9.24
2028	3.92	4.36	4.36	5.35	4.77	11.01	9.81	7.12	8.45	7.76	6.72	4.08	3.73	9.58
2029	4.04	4.53	4.53	5.53	5.04	11.52	10.24	7.44	8.9	7.95	6.89	5.69	4.53	9.92
2030	4.16	4.7	4.7	5.71	5.32	12.06	10.7	7.77	9.38	8.14	7.08	9.44	7.04	10.28
2031	4.28	4.88	4.88	5.9	5.61	12.63	11.18	8.13	9.89	8.35	7.27	2.37	2.41	10.65
2032	4.41	5.07	5.07	6.1	5.92	13.23	11.69	8.5	10.42	8.56	7.47	2.55	2.61	11.04
2033	4.55	5.27	5.27	6.31	6.25	13.87	12.22	8.89	10.98	8.78	7.68	2.75	2.84	11.45
2034	4.69	5.48	5.48	6.54	6.6	14.53	12.79	9.3	11.56	9.01	7.9	2.98	3.11	11.89
2035	4.84	5.7	5.7	6.77	6.97	15.24	13.38	9.73	12.18	9.26	8.12	3.24	3.42	12.34
2036	5	5.93	5.93	7.02	7.36	15.98	14.01	10.18	12.82	9.51	8.36	3.57	3.79	12.82
2037	5.17	6.17	6.17	7.28	7.77	16	14.67	10.66	13.51	9.77	8.61	3.96	4.25	13.31
2038	5.35	6.42	6.42	7.56	8.21	16	15.37	11.16	14.23	10.05	8.88	4.95	5.48	13.84

ANNEXURE B

B.1 Empirical relations to calculate Vehicle Operating Cost for various MT vehicles
(Clause 6.6, IRC: SP: 30-2009)

Table B.1.1 Empirical relations to calculate Vehicle Operation Cost for Cars

S. No.	VOC Component	Equation
1	Speed	$V = 78.58 - (0.764 * RF) - 0.00183 * (RG - 2000)$
2	Fuel	$FC = 21.85 + (504.15/V) + 0.004957 V^2 + 0.000652 * RG + 1.0684 * RS - 0.3684 * F$
3	Lubricating Oil	$EOL = 1.7048 + 0.03319 * RF + 0.0005241 * (RG/W)$
4	Maintenance Labour	$LC = 0.5498 * SP$
5	Spare parts cost	$SP = 0.0018 * (RG - 2000) * 10^{-5} * NP$
6	Utility	$UPD = 6.187 * V$

Table B.1.2 Empirical relations to calculate Vehicle Operation Cost for Buses

S. No.	VOC Component	Equation
1	Speed	$V = 60.32 - (0.4573 * RF) - 0.00109 * (RG - 2000)$
2	Fuel	$FC = 32.97 + (3904.64/V) + 0.0207 * V^2 + 0.0012 * RG + 3.3281 * RF - 1.7769 * FL$
3	Engine oil	$EOL = 1.146 + 0.00398 * RF + 0.0021 * (RG/W)$
4	Spare parts cost	$SP = e^{-10.44 + 0.007373 * RF + 0.0000723 * RG + 1.925 * W} * NP$
5	Maintenance cost	$LC = 0.5498 * SP$
6	Utility	$UPD = 28.07 + 15.1476 * V$
7	Crew wages	$CW = 93867 / UPD$

Table B.1.3 Empirical relations to calculate Vehicle Operation Cost for Light Commercial Vehicles

S. No.	VOC Component	Equation
1	Speed	$V = 62.85 - (0.5604 * RF) - 0.00111 * (RG - 2000)$
2	Fuel	$FC = 21.28 + (1615.327 / V) + 0.0245 * V^2 + 0.001524 * RG + 5.377 * RF - 0.8268 * FL$
3	Engine oil	$EOL = 1.0635 + 0.0257 * RF + 0.000171 * (RG/W)$
4	Spare parts cost	$SP = e^{-10.9278 + 0.000141 * RG + 3.493 * W} * NP$
5	Maintenance cost	$LC = 0.3692 * SP$
6	Utility	$UPD = 28.773 + 2.181 * V$
7	Crew wages	$CW = 599.15 / UPD$

Table B.1.4 Empirical relations to calculate Vehicle Operation Cost for Trucks

S. No.	VOC Component	Equation
1	Speed	$V = 55.53 - (0.4952 * RF) - 0.00098 * (RG - 2000)$
2	Fuel	$FC = 4.08 + (3904.64/V) + 0.0207 * V^2 + 0.0012 * RG + 3.3281 * RS - 1.7769 * FL$
3	Engine oil	$EOL = 1.73 + 0.042 * RF + 0.0003 * (RG/W)$
4	Spare parts cost	$SP = e^{-1.03677 + 0.0001413 * RG + 3.4930/W} * NP$
5	Maintenance cost	$LC = 0.3692 * SP$
6	Utility	$UPD = 68.12 + 5.1637 * V$
7	Crew wages	$CW = 599.15 / UPD$

Table B.1.5 Empirical relations to calculate Vehicle Operation Cost for Multi-Axle Trucks

S. No.	VOC Component	Equation
1	Speed	$V = 46.65 - (0.4159 * RF) - 0.00083 * (RG - 2000)$
2	Fuel	$FC = 141 + (2695.79/V) + 0.0517 * V^2 + 0.0035 * RG + 17.75 * RS - 5.40 * FL$
3	Engine oil	$EOL = 2.354 + 0.05701 * RF + 0.0038 * (RG/W)$
4	Spare parts cost	$SP = e^{-1.09278 + 0.0001413 * RG + 3.4930/W} * NP$
5	Maintenance cost	$LC = 0.3692 * SP$
6	Utility	$UPD = 70.38 + 5.3349 * V$
7	Crew wages	$CW = 718.98 * UPD$