Development of Pavement Maintenance Management System (PMMS) for Urban Roads

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Submitted by

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CERTIFICATE

I, Tanuj Chopra, hereby certify that the work presented in the thesis entitled "**DEVELOPMENT OF PAVEMENT MAINTENANCE MANAGEMENT SYSTEM (PMMS) FOR URBAN ROADS**", in fulfilment of the requirement for the award of the degree of **DOCTOR OF PHILOSOPHY** in the Department of Civil Engineering, Thapar University, Patiala, is an authentic record of my own work carried out during the period from July 2010 to July 2017 at this university under the supervision of **Dr. Manoranjan Parida** and **Dr. Naveen Kwatra**.

The matter presented in this thesis has not been submitted for the award of any other degree in any university.

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(TANUJ CHOPRA)

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LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transport Officials
AF	Activation Function
AHP	Analytic Hierarchy Process
ANN	Artificial Neural Networks
AXLEYR	Number of Vehicles Axle Per Year
BI	Bump Integrator
CA_i	Cracking Progression
CBR	California Bearing Ratio
CR_i	Initial Cracking Area
CRRI	Central Road Research Institute
CSALYR	Cumulative Standard Axles Per Year
DBM	Dense Bituminous Macadam
DBSD	Double Bituminous Surface Dressing
DF	Drainage Factor
DI	Distress Index
ESAL	Equivalent Single Axle Load
ESALF	Equivalent Single Axle Load factor
FHWA	Federal Highway Administration
FWD	Falling Weight Deflectometer
GA	Genetic Algorithm
GIS	Geographic Information System
GP	Genetic Programming
goal	Performance Goal
HDM-4	Highway Development and Management System
HDM-III	Highway Design and Maintenance Standards Model
HUDA	Haryana Urban Development Authority
hn	Hidden Neurons
IAPMS	Integrated Airport Pavement Management
IRI	International Roughness Index
IRI_i	Roughness Progression

IRR	Internal Rate of Return
LCCA	Life Cycle Cost Analysis
LED	Level of Economic Development
LVR	Low Volume Roads
lamda	Number of Children produced
lr	Learning Rate
M&R	Maintenance and Rehabilitation
MORT&H	Ministry of Road Transport and Highways
MPI	Maintenance Priority Index
MSNR	Reduced Modified Structural Number due to Cracking
MSS	Mix Seal Surfacing
m	Environmental Factor
mu	Population Size
MT	Motorized Traffic
NH	National Highways
NHAI	National Highway Authority of India
NMT	Non-motorized Traffic
NPV	Net Present value
OPCI	Overall Pavement Condition Index
PAGE	Pavement Age since last renewal
PC	Premix Carpet
PCI	Pavement Condition Index
PCSE	Passenger Car Space Equivalents
PH_i	Initial Pothole Area
PI	Priority Index
PMGSY	Pradhan Mantri Gram Sadak Yozna
PMS	Pavement Management System
POT_i	Pothole Progression
PSI	Present Serviceability Index
PSR	Present Serviceability Rating
PWD	Public Works Department
R^2	Coefficient of Determination
RA_i	Ravelling Progression
RCI	Road Condition Index

RDME	Road Deterioration and Maintenance Effects
RI	Roughness Index
RMSE	Root Mean Square Error
RNIS	Road Network Information System
Rs.	Indian Rupees
RSL	Remaining Service Life
RUC	Road User Cost
SAI	Structural Adequacy Index
SBSD	Single Bituminous Surface Dressing
SCRIM	Sideways Coefficient Routine Investigation Machine
SDBC	Semi Dense Bituminous Concrete
SF	Special Factor
SFC	Sideways Force Coefficient
SH	State Highways
SNCK	Modified Pavement Strength
SRV	Skid Resistance Value
TLF	Time Lapse Factor
TVF	Traffic Volume Factor
UPMS	Urban Pavement Management System
VDF	Vehicle damage Factor
VOC	Vehicle Operating Costs
VCI	Visual Condition Index
WCPA	Western Cape Provincial Administration
WMM	Wet Mix Macadam

ABSTRACT

Roads are the fundamental infrastructure requirement for the development of a nation, contributing to the National economy. The availability of good and serviceable roads is as important in an urban area as other services like water supply, electricity, drainage, telecommunication etc. Any shortfall in the serviceability of urban roads immediately results into great dissatisfaction among the commuter and the urban population. Regular Maintenance of these city roads is very much essential and should not be neglected, particularly in developing countries like India. The magnitude of work involved in maintaining the road networks to required serviceability is very large but the budget available for the maintenance is generally not enough to meet the requirements. Most of the maintenance and rehabilitation treatments provided on the urban roads is based upon the experience or judgment of the department engineers only. Therefore, there is a need of develop an effective scientific methodology and programs for deciding the optimum maintenance and rehabilitation strategies for the city road networks. Development of an effective Pavement Maintenance Management System (PMMS) would provide various project and programme level analysis and will also help to calculate the remaining service life of pavements & to prioritize the urban road sections based upon the available maintenance funds. Rawat (1998) & Shah (2016) stated that the urban roads in India have different types of problems as compared to other categories of road such as higher repetitions of traffic with problem of overloading, encroachment on the road side area, lack of proper drainage system which may lead various distresses in pavements, and various utility services which necessitate frequent digging thereby disturbing homogeneity of pavement structure. Therefore, there is a urgent need to develop a Pavement Maintenance Management System (PMMS) for the urban road networks, as it constitutes around 9% of total road network length in India, which would be useful to the city agencies such as Municipal Corporations, Public Works Department & other agencies involved in planning & executing pavement maintenance strategies in a scientific manner under both the options of constrained & unconstrained budget.

The proposed PMMS methodology includes: identification and selection of the urban road network, collection of field data and database management, and calibration and validation of HDM-4 pavement deterioration models for local conditions. The procedures and

equipments used for collection of various kinds of field data on sixteen pavement sections have been described. The data for vehicle fleet plying on the road network, maintenance and rehabilitation activities, cost data for various types of M&R works, and the road user cost data, as obtained from field and relevant government publications has been presented. The time series pavement distress data of cracking, ravelling, potholes, rutting and roughness have been collected for the year 2012, 2013, 2014 and 2015. The HDM-4 road deterioration models have been calibrated for the selected urban road sections under local conditions using the time series pavement distress data collected for the year 2012, 2013, 2014 and 2015. The calibrated HDM-4 pavement deterioration models, considered in this study have been validated by comparing the values of distresses predicted in year 2014 & 2015 by the HDM-4 model with those observed in the field in year 2014 & 2015 , for all the road sections of urban network. The difference between the observed and predicted distress values is not statistically significant at 5% level of significance. Therefore, the calibrated deterioration models have been used for time series prediction of distresses on all pavement sections. In the present study, different aspects of project and network level PMMS have been studied using various modules of HDM-4. The project level analysis included determination of optimum maintenance & rehabilitation, comparison of scheduled and condition responsive maintenance strategy and estimating remaining service life of urban road sections. The optimum maintenance strategies have been determined based on highest NPV/Cost ratio. The network analysis included life cycle-cost analysis of urban road network giving an unconstrained budget works programme, optimization of resource allocation for maintenance giving constrained works programme and prioritization of urban road sections for maintenance on the basis of decreasing NPV/Cost ratio.

The two emerging soft computing techniques; neural network and GP have also been applied on the data set of 16 road sections of Patiala City for the prediction of pavement distress. Four models (*i.e.*, Model1, Model2, Model3 and Model4 for Cracking Progression (*CA*), Ravelling Progression (*RA*), Potholes Progression (*POT*) and Roughness Progression (*IRI*), respectively) have been developed for the prediction pavement distress. In the present study, all the developed models have the value of $R^2 > 80\%$. Neural network and GP models have been developed and compared with the help of fitness functions *i.e.*, Coefficient of Determination (R^2) and Root Mean Square Error (RMSE). It has been observed that GP models provide the value of R^2 is higher and RMSE is less as compared to neural network, when applied on validation data sets. The next objective of the present study is to reveal the role of the Geographical Information System (GIS) technology in the enhancement of urban PMMS. A variety of spatially integrated data are important to pavement management decision making.

Thus, the thesis presents a scientific approach for the development of pavement maintenance management system for the urban road networks. The suggested approach could be adopted for development of PMMS for other cities in India and for other categories of roads such as National Highways, State Highways, Major District Roads & Village Roads by using the inputs of PMMS methodology used in this study. This study would be very beneficial to the various government local agencies of Patiala city in defining & developing road maintenance strategies & work standards for maintenance in a systematic & scientific manner and to ensure the proper utilization of the available maintenance budgets by optimising the investment decisions based upon certain economic indicators such as NPV/cost ratio.

CHAPTER 1

PAVEMENT MAINTENANCE MANAGEMENT SYSTEM (PMMS): AN INTRODUCTION

1.1 INTRODUCTION

Road transport has been acknowledged as a major lifeline for the development of the major infrastructure leading to overall economic growth of the country. Road pavements needs the major share of the capital investment and require continuous maintenance to keep them in a serviceability condition. With lack of maintenance at right time, pavements deteriorate rapidly, leading to higher Vehicle Operating Costs (VOC), increased number of accidents and reduced level of serviceability. Delayed maintenance will often involve major rehabilitation, and even reconstruction, costing many times more than the timely maintenance treatment carried out earlier. Maintenance activities need to be triggered at suitable intervention level so that the pavements can be maintained in a scientific manner at a lower cost. The presence of adequately functional and serviceable urban roads is one of the basic necessities of life in any town or city, as important as clean water, electricity *etc.*, (IRC Annual Session 1987). The example shown in Fig. 1.1 shows the effect of ignoring the road maintenance. It shows the life cycle costs of construction, maintenance and vehicle operation under different maintenance criteria's. With traffic of about one thousand vehicles per day, a road in good condition will require about 2% of the total discounted costs to be spent on maintenance. However, if maintenance funds are reduced, the pavement will start to crack and potholes will gradually appear. With this level of deterioration, VOC are likely to increase by about 10%. If there is a complete neglect of maintenance, a paved road will eventually start to disintegrate and annual VOC will increase by about 40% (Robinson 1998). A systematic scientific methods, therefore, needs to be considered for providing the Maintenance and Rehabilitation (M&R) strategies throughout the design life of the highway. The agencies responsible for maintaining the road networks should plan the maintenance of the road network by providing suitable timely maintenance activities at a proper intervention level so as to maintain the network to the required level of serviceability with the minimum cost for the present day's requirements of large traffic volumes and heavy traffic loads.

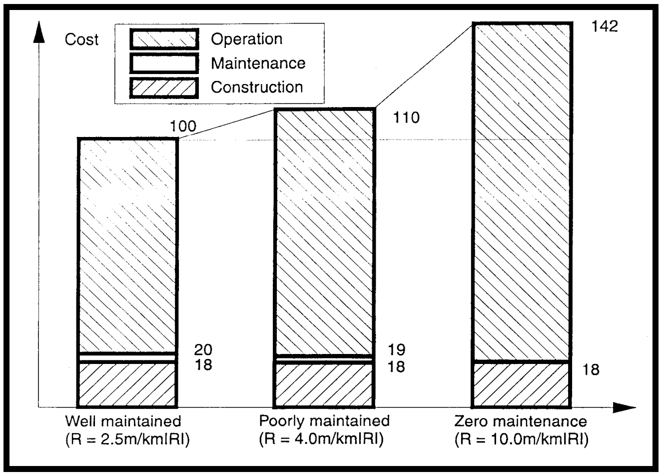


Fig. 1.1: Change in Discounted Life Cycle Costs for Different Levels of Pavement Maintenance

In India, the total length of the urban roads is about 4.118 lakh Kilometers (MoRT&H 2012). The urban roads cater to very heavy traffic volume and large amount of freight and goods transport; therefore any damage or loss of functionality caused in urban roads results in a huge loss to the road user in terms of valuable time and comfort. These damages generally also require a large sum of money to rectify. The responsibility for repair, maintenance and upkeep of urban roads falls under the jurisdiction of Municipal Corporation, Municipal Boards, Cantonment Boards and Port Trusts which are statutory bodies in urban areas. Ministry of Road Transport & Highways (MoRT&H) is a Government of India (GoI) undertaking organization responsible for framing policies for Road Transport, National Highways and Transport Research with a view to increase the mobility and efficiency of the Road Transport system in India. MoRT&H 2004 documented the guidelines for maintenance management of primary, secondary urban roads and the prevailing maintenance norms/practices for different road categories are mentioned, here. The details regarding data collection and analysis are also discussed. The methods for selection of optimum maintenance strategies and prioritization of sections for maintenance are also explained in this document. The urban roads are however hard to maintain, since they cater to very heavy but uneven traffic. In addition, the trip lengths may vary significantly, and a large number of diversions to residential or industrial centers are generally encountered. Thus, a lack of adequate riding service in an urban road generally causes significant displeasure to the commuters and riders. It is therefore of utmost importance that these roads are maintained to ensure best possible quality of service and convenience to the road users. The following are the major problems in urban roads:

- Drainage problem is a big problem in urban roads. Since urban roads generally have no natural drainage, the water accumulated due to rains is not easily disposed of. This water can seep into the subgrade and cause erosion. The erosion of side slopes and overall reduction in pavement strength may also be noted. A well designed drainage system is thus pivotal to urban roads to safely take out the water which can cause structural damage to the pavement**. Brain et al. (2005)** concluded that the inclusion of drainage layer affected positively to subgrade resilient modulus, effective pavement modulus and effective structural number of the selected sections under study. **Grover and Veeraragavan (2010)** concluded that the rate of deterioration of the functional parameters viz. roughness, cracking and ravelling is faster by 41%, 20% and 25% respectively as compared to pavement sections with good drainage.

  However, it is generally noticed that in most of the city roads, even the existing drainage systems are under-maintained. **Prakash (2009)** developed a Maintenance Management System (MMS) for an identified urban road network of Patna City using HDM-4. In monsoon season, the storm water tends to stand on the roads for a long period of time, which causes local cavities and surface distresses like potholes in the roads. In some cases, the leakage of sewer waste from the sewer pipes may cause cavities under the roads. The effect of a poorly designed drainage system is visible easily in Patna, which lies in a saucer (bowl) like basin, into which three rivers drain. As a result, the road network of this city often suffers from temporary outages in functionality and standing water and traffic jams during heavy rains. This is a side effect of an inadequate and poorly designed drainage system, which results in major loss of riding quality and user satisfaction; it also creates an unwanted economic burden, as large sum of money is generally required for repair and rehabilitation of the road sections. **Choudhary et al. (2011)** highlighted the importance of drainage in performance of flexible pavement by describing the effect of various distresses on flexible pavements due to inadequate drainage facilities. **Agarwal et al. (2011)** evaluated the pavement performance considering the roughness as the distress parameter with different drainage quality. The analysis concluded that there was a significant increase in pavement roughness with increase in pavement age, traffic growth and saturation time for different drainage quality. Literature reveals that it is important that the drainage system works properly so that surface and ground water can drain freely and quickly away from the road or under the road. The object of drainage maintenance is to ensure that drainage system elements remain free of obstructions, and retain their intended cross section and grades.

- Heavy traffic volume and abrasion of road surface is a common problem in urban roads. Not only the urban roads cater to a large variety of vehicular traffic, the traffic volume is also quite large generally. Combined with mixed traffic volume, it often creates a situation of frequent start and stops in an urban road. The maneuvers such as sudden braking and starting effect, sharp turns *etc*. often cause localized corrugations and abrasion in the road sections. This results in reduced of pavement thickness and loss of riding quality and comfort, causing significant discomfort to road users**. Reddy and Veeraragavan (1995)** developed a practical method for the maintenance management of rural (non-urban) highways and developed models for predicting structural condition and functional condition of the flexible pavement. The equations were developed for predicting the rebound deflection after an expected number of traffic load repetitions for the pavements overlaid with asphalt concrete and bituminous macadam (BM) surfacing. This problem is more acute at roundabouts and intersections, where frequent forces of acceleration and deceleration harm the road.
- Due to paucity of land in urban areas, the same right of way needs to be utilized for carrying the traffic at the top and carrying the services like sewer lines, water pipes, telephone lines *etc.*, underground. Further, as the city population increases, the capacity of these services also needs to be increased; hence they are added subsequently in successive stages. Many times, this addition requires partial disruption in road services by cordoning off some part of the carriageway. The coordination between different departments and overlap of alignment of major services causes newer encroachments on ROW, which may result in road damage. The leakage from water pipes or sewer pipes due to improper joints may result in development of localized soft distress spots. Improper filling of roads after cutting (to install new pipelines) may result in unintended unevenness that deteriorates the riding quality.
- Widening of Roads is often required as the traffic load on the roads increases beyond their design capacity. This has to be accomplished in successive stages depending on the financial resources and manpower available, all the while causing minimum inconvenience to road users.

- Road side encroachment by street vendors, commercial activities by shops, dhabas *etc*. and by laborers and migrant workers for residential purposes often result in the reduction of carriageway width and inconvenience to road users.

1.2 PAVEMENT MAINTENANCE MANAGEMENT SYSTEM (PMMS)

A Pavement Management System is a set of defined procedures for collecting, analyzing, maintaining, and reporting pavement data, to assist the decision makers in finding optimum strategies for maintaining pavements in serviceable condition over a given period of time for the least cost.

1.2.1 Necessity of PMMS

The urban roads have the major share of urban infrastructure investment, *i.e*., 55.8% of the total. The total capital expenditure requirement for urban roads is estimated to be Rs 17.3 lakh crore, and operation & maintenance requirements is estimated to be Rs 3.8 lakh crore for the year 2030 (Shah 2014). The road network built with a huge investment is showing signs of deterioration and disintegration. Complacency and inadequacy of road maintenance have caused irreparable damage to economic growth rate, as poorly maintained roads cause congestion, delay, road accidents, and higher vehicle operating costs. The following are some of the major deficiencies in the Indian road network that highlight the need for PMMS:

1.2.1.1 Deficiencies in Design Standards

The majority of roads in the country are poorly designed, deficient with regard to design standards, geometrics, safety aspects and road user comfort conditions. This is due to limited resources available at any time. This means we need to stage construction. The pavements are designed for an initial service life of about 15 years (IRC: 37-2012) and then strengthening is provided as the traffic demand increases. However, many roads do not fulfill even their design life due to poor management owing to the financial constraints.

1.2.1.2 Growing Road Transport Demand

India has been witness to a massive growth in road traffic since independence. The vehicle population has grown from just 3 lakh in 1951 to about 450 lakh now. Further, the quantity of goods plied on road transport has increased by more than seven times from 600 lakh tonnes to 40,000 lakh tonnes at present. The share of road transport in passenger movement and freight movement has increased by 20% to 85% and 20% to 70% respectively during the last 60 years.

Table 1.1 gives the growth in number of vehicles over the last 60 years.

Table 1.1: Growth of Vehicles during Last 60 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
2015	110000*	7500*

* Estimated figures

Source: MORT&H [2001c], and NHAI@2013

1.2.1.3 Lower Quality of Roads

India has a vast road network; however, the quality of roads largely remains poor. More than 50% of the road network is still unpaved. Owing to the lack of any significant management other than repeated overlays, the existing road network has aged and deteriorated rapidly, leading to appearance of numerous kinds of distresses viz. cracking, ravelling and potholing on road surface. These distresses, under the combined action of moving traffic and environmental factors have enhanced the need for Pavement Management strategies.

1.2.1.4 Increased Traffic and Axle Loads

Traffic on the Indian roads, in terms of volume and axle loads, is increasing at an alarming rate. The annual growth rate is estimated to be of the order of about 10% (MORT&H 2001c). This phenomenal growth in vehicle population and road usage has put a tremendous strain on the existing road network. According to ‘Road Damage Formula’, pavement that can last for 10 years without overloading will last only for 6.5 years and 3.5 years, if there is 10 percent and 30 percent overloading respectively. There has been considerable increase in the axle loads carried by freight vehicles. Despite the regulations which cap the axle load at 10.2 tons, vehicles of axle load 18-22 tons are plying on these roads. Thus until the regulations are more strictly enforced, the management strategies are important to increase the life of the roads.

1.2.1.5 Inadequate Allocation of Funds

The present Allocation of funds is only 60% of the actual requirement of the funds required for proper maintenance. Any neglect of maintenance activity is self-defeating as one Rupee spent on maintenance saves 2 to 3 Rupees in vehicle operating cost (MORT&H 2001b). Consequently, the gap between the allocation and requirements has only widened over the last few years, which is grave news given the fact that the traffic volume and weight are both growing rapidly. Further, given the maintenance activities are generally never planned in advance, there is also tendency by the decision-makers to apply random cuts when faced with resource constraints.

Following the lack of adequate and timely maintenance measures, the pavement condition may deteriorate very sharply from ‘good’ to ‘poor’ during a very short span of pavement life, leading to 4-5 times higher fund requirements for rehabilitation of the pavement at that stage. Thus, if maintenance and rehabilitation is performed during the early stages of deterioration, before a sharp decline in pavement condition, over 75% of the maintenance costs can be avoided (Shahin 1994).

1.3 HIGHWAY DEVELOPMENT AND MANAGEMENT SYSTEM (HDM-4)

The Highway Development and Management System (HDM-4) developed by the World Bank is a major tool for developing pavement maintenance management system capable of performing technical and financial appraisals of road investments, investigating pavement programs, and analyzing preservation strategies. The effectiveness of the HDM-4 is dependent on the proper calibration of its distress prediction models and its adaptability to the local conditions. The scope of the HDM-4 tool has been broadened considerably beyond traditional project appraisals, to provide a powerful system for the analysis of road management and investment alternatives. The HDM-4 provides maintenance tools for the project level analysis, road work programming under constrained budgets, and for strategic planning of long term network performance and expenditure needs. It is designed to be used as a decision support tool within a road management system. The pavement deterioration models incorporated in the HDM-4 need to be calibrated for the local conditions with validation. The calibrated models can be used for the perdition of future pavement deterioration. The ‘Project analysis’, ‘Programme analysis’ & ‘Strategy analysis’ application module of HDM-4 are used to develop PMMS at network & project level. **Aggarwal et al. (2004) & Jain et al. (2005)** calibrated HDM 4 pavement deterioration models for National Highways in India. The pavement deterioration models were calibrated to give the same rate of deterioration as determined by models developed by CRRI from the study of existing pavement sections carried out under pavement performance study project. **Thube (2006, 2013)** calibrated and validated the various pavement deterioration models incorporated in HDM-4 for sixty one in-service rural road sections located in different terrains of study area for local conditions and extensive time series pavement distress data were collected in the year 2004, 2005 and 2006. **Aggarwal et al. (2004)** developed a HDM-4 based PMS for an indentified National Highway Network to help the highway engineers in charge for maintaining the highway network and the authorities in charge for distributing funds, in making reliable and economic decisions. The PMS was developed at Project level and Network level using the ‘Project Analysis’ and ‘Programme Analysis’ component of HDM-4 respectively. **Shankar et al. (2010)** carried out detailed analysis for rural road stretches in Warangal district using HDM-4 for responsive and schedule maintenance and recommended the best alternative. **Odoki et al. (2012)** described the adaptation and calibration of HDM-4 to accurately model pavement performance and road user effects in England.

1.3.1 Requirements of Input Data

The input data to HDM-4 is held in four data managers, which are described below:

- **Road network -** Defines the section ID with description, surface class and pavement type, length of the section, width of the carriageway, traffic & speed flow type, climate zone, road class, Motorized and non-motorized traffic with AADT year.
- **Vehicle fleet -** Defines the name & class of vehicles with category along with basic characteristics such as passenger car space equivalent, operating weight and economic unit costs.

- **Road works standards –** Defines various maintenance and improvement standards with designed intervention levels either as scheduled or responsive treatment, along with their unit costs, which will be applied to the different road sections to be analyzed.
- **HDM configuration -** Defines the traffic flow, speed flow, currencies and climate zones along with section aggregate data and tables.

1.3.2 Technical Models

Technical analysis within the HDM-4 is undertaken using the following four sets of models:

- **Road Deterioration (RD) -** Predicts pavement surface deterioration in terms of various distresses such as cracking, rutting, roughness, potholes, structural number and raveling for various types of pavements such as flexible, rigid, and granular roads.
- **Works Effects (WE) -** provides the effects of road maintenance or improvement on pavement condition and determines the corresponding costs.
- **Road User Effects (RUE) -** Determine costs of vehicle operation, and travel time. In the year 1982, CRRI completed the RUE study under the sponsorship of Ministry of Surface Transport (MOST), GoI **(CRRI 1982)**. In this study, a large number of commercial and private vehicles were identified. Then the data on the operating cost of these vehicles have been gathered along with the design parameters of the roads on which these are operated. By analyzing this data, relationships were developed between the road design standards and vehicle operation costs. This study was updated in 1992 in order to incorporated the new vehicles entered the Indian traffic (**Kadiyali 1992, 1993).** Subsequent to the above study, many more new variants/ models of passenger cars and goods vehicles came into Indian market. Therefore, to further update the relationships between the road user cost and the design parameters of the roads, a new study was commissioned at CRRI by the MORT&H, GoI. As a part of this study, which has been completed in the year 2001, measurements of speeds as well as vehicle operating cost has been accomplished and analyzed strategically (**CRRI 2001, Reddy 2003)**.

1.3.3 Application Modules

There are three main application modules in HDM-4, *i.e.*, Project Analysis, Program Analysis, and Strategic Planning **(Kerali 2000, Shah 2012, 2016)**. These are described below:

- **Project analysis –** In the Project level module of HDM-4, economic analysis of one or more road projects and its investment options can be performed. Road sections with defined maintenance and rehabilitation strategies are analyzed over a specified design life time. Project analysis can be used to estimate the economic viability of the maintenance decision by performing the life cycle cost analysis (LCCA) of road agency cost together with estimates of road user costs to calculate the total transportation cost.
- **Program analysis –** In the Network level application of HDM-4 maintenance work programme for selected road sections are identified and are assigned various maintenance works applicable for that particular pavement type. Economic Indicators such as NPV/ Cost are calculated for each strategy. Program analysis provides a schedule of optimum pavement maintenance and rehabilitation strategies, which can be performed as per the availability of maintenance funds. Maintenance work programs are generated by HDM-4 under both the constrained & unconstrained budget options
- **Strategy analysis –** In the Strategic analysis of HDM-4, the analysis of a selected urban road network is carried out as a whole. This network level application is used for strategic planning to prepare a planning estimates of funding needs for the maintenance and improvement works of the road network.

Naidu et al. (2005) made an attempt to select optimum maintenance strategies and developed PMMS based on life cycle costs using HDM 4 for the inner ring road of Delhi. The network of study area consisted of major arterial roads for Delhi having 48 km (96km both directions) road length with six lanes divided carriageway. Project analysis and programme analysis components of HDM 4 were used for developing PMMS. The major difference between strategy and program analysis is the manner in which the road links and sections are identified. Program analysis deals with individual links and sections that are unique physical units, identifiable from the highway network throughout the analysis. In strategy analysis, the highway network essentially loses its individual link and section characteristics by grouping all road segments with similar characteristics into the highway network categories.

1.3.4 Interfaces to External Systems

The HDM-4 system design is modular in structure to enable highway agencies to implement the HDM-4 application modules independently within their pavement management systems. The system is designed to interface with external road network information systems through its databases. Data transformation rules may need to be implemented for converting the data held in the external database to the format used by HDM-4. Data required by HDM-4, such as pavement deterioration calibration factors should be inserted as pre-defined default values according to the type of pavement, road class and other defined factors. These include data on vehicle fleet characteristics, road maintenance and improvement standards, unit costs and economic analysis parameters such as discount rate and analysis period *etc*., (Kerali 2000).

1.3.5 Life-cycle Analysis

HDM-4 simulates the total life cycle conditions and costs for an analysis period under specified circumstances. The model stimulates, for each pavement section, year-by-year, the pavement condition and resources used for maintenance under each strategy, as well as the vehicle speeds and physical resources consumed by vehicle operation. Interacting sets of costs related to those incurred by the road administration and those incurred by the road user, are added together over time in discounted present values. Economic benefits are then determined by comparing the total cost streams for various maintenance alternatives with a base alternative, usually representing minimum routine maintenance (Odoki and Kerali 2000).

1.4 OBJECTIVES

The following are the primary objectives of this study:

1. Development of a database consisting of inventory data, pavement condition data, traffic data and other necessary data of the selected Urban Road Network.
2. Identification of an evaluation system that assists in making timely cost effective decisions related to the maintenance and rehabilitations of pavements using pavement performance models of HDM-4.
3. To develop pavement performance models using soft computing techniques.
4. Developing a method of prioritizing segments in a pavement maintenance program.
5. To develop a Geographic Information System (GIS) for representing the PMMS.

1.5 ORGANIZATION OF THE THESIS

The research work has been carried out keeping these above said objectives in view. The thesis presents this work in six chapters. Chapter wise summary of the thesis is given below:

Chapter - 1 presents the statistical data of Indian road network, urban road network, road condition scenario in India, classification of urban roads, various deficiencies and inadequacies of urban road. This chapter also presents the overview of PMMS and the role of HDM-4 for developing PMMS.

Chapter - 2 presents the review of the literature. It discusses the various works done on PMMS using HDM-4 model.

Chapter - 3 presents a detailed methodology of the development of PMMS for the selected road network. It includes identification and selection of the road network and division of the same into homogeneous pavement sections. It also presents in detail the methodology adopted for collection of various kinds of data required for the development of PMS, such as highway network data, vehicle fleet data, maintenance & rehabilitation activities data, and the cost data. The progression of various pavement distresses like roughness, Benkelman beam deflection, rutting, ravelling, cracking & pothole area for the selected urban road network for the three consecutive years has been presented in this chapter. The maintenance strategies suggested based on nature of distresses for the selected urban sections and the methodology of calibration of HDM-4 pavement deterioration models for the local conditions has also been described. A statistical comparison of the HDM-4 predictions and the actually observed values in the field in respect of pavement condition data is also provided for validation of the calibrated HDM-4 pavement deterioration models.

Chapter - 4 The PMMS developed at network level and project level using project analysis and programme analysis of HDM-4 tool along with the method of prioritization for the selected urban transport network have been presented in this chapter.

Chapter - 5 deals with the application of Genetic Programming (GP) and Neural Network (NN) models for making the prediction models for the pavement deterioration in terms of the roughness progression. This chapter also presents the application of GIS to urban pavement maintenance management system developed for urban roads. The results of analysis have been displayed graphically in GIS which is considered a powerful tool in assisting decision makers for effectively identifying, planning and scheduling maintenance works.

Chapter - 6 summarizes the conclusions drawn out on the basis of the present study. Some recommendations for further scope of research in this area are also given in this Chapter.

CHAPTER 2

REVIEW OF THE LITERATURE

2.1GENERAL

This chapter reviews the studies relevant in the context of the present work. In particular, development done so far in implementing the PMMS in India and the international PMMS scenarios has also been reviewed. An extensive literature survey has been carried out and presented here to keep abreast with the latest techniques used for modelling the different components of PMMS viz. pavement evaluation, pavement performance prediction, optimization of resource allocation, pavement drainage and prioritization methods for maintenance.

2.2REVIEW OF LITERATURE

2.2.1 Database for Pavement Maintenance Management System

Database is vital component for the success of any PMMS study. Without good data, it is not possible to conduct proper maintenance management analyses or monitoring of the pavement performance. Problems with data are one of the main causes of failure of maintenance management system. Data regarding pavement inventory, traffic characteristics, drainage condition, pavement history, maintenance standards, pavement distresses and schedule rates are required for developing PMMS.

Tavakoli et al. (1992) presented a PMMS for small communities for supporting the decision of scheduling and budgeting of various levels for the repair of roadways. This was a based on guidelines of "Road Surface Management for Local Government" manual for the U.S. Department of Transportation. They had considered the following data base:

- Section identification (Section number, name, functional class, jurisdiction)
- Pavement characteristics (type, width, drainage system, curb height, number of inlets)
- traffic flow (average daily traffic, % trucks
- Utilities and historical information.

The maintenance history data of each section contains:

- maintenance activity
- pavement type
- rate of thickness
- date and unit cost.

They had planned the following M&R strategies based upon data collection of deflection and structural number of pavement:

A. Routine Maintenance	• Crack Sealing • Skin Patching • Local Repairs • Strategy C actions as necessary
B. Preventive Maintenance	• Strategy A and C actions as necessary • Surface Seals • Thin Overlays
C. Deferred Actions	• Patching of High severity, Potholes, shoving, Corrugations and Rutting
D. Rehabilitation	• Strategy A, B and C as necessary • Removal of Portion of surface if necessary • Structural Overlay
E. Reconstruction	• Strategy D actions as necessary • Remove/Replace entire pavement structure • Geometric, Safety and traffic improvements.

They had also done calculations on:

- Priority rating for all sections
- Estimates the total maintenance and rehabilitation costs
- Priorities specific sections
- Computes the long-range goals

The emphasis on this work was to develop user-friendly and practice oriented PMMS which results in more effective allocation of available funds and better estimates of the future needs.

Shah et al. (2013) developed a combined Overall Pavement Condition Index (OPCI) based upon distress data collected for the selected network of Noida roads. The study area consisted of 10 road sections constituting 29.92 km of Noida city. The methodology included identification of urban road sections, pavement distress data collection, development of individual distress index and finally developing a combined OPCI for the network. The four performance indices viz. Pavement Condition Distress Index ($PCI_{Distress}$), Pavement Condition Roughness Index ($PCI_{Roughness}$), Pavement Condition Structural Capacity Index ($PCI_{Structure}$) and Pavement Condition Skid Resistance Index (PCI_{Skid}) were developed individually. They combined all these indices together to form an OPCI giving importance of each indicator. They concluded that the proposed index was expected to be a good indicative of pavement condition and performance.

Thube (2013) developed and calibrated HDM-4 pavement deterioration models for Indian roads. These models were developed for thin-surfaced roads of India and they claimed that these models can be adjusted to any type of terrains by varying the values of calibrated factors of distress type. They had collected data for all the schemes (like plain, rolling and mountains) from the Uttarakhand, India. The data was collected in terms of cracking, ravelling, rut depth, pothole, edge break and roughness progression. They had identified various road sections of selected state and data had been collected during two continuous years (2004-2005). The sample road sections consist of 1 km length and cracking, ravelling, potholes and edge break had been measured by visual condition survey. Their proposed procedure for calibration of pavement performance models was based on the coefficient between the observed years of occurrence as distress to the years of occurrence as predicted by the uncalibrated models and for progression models, it had been done by minimising the squares of differences between the observed data or sum of differences between the estimated and observed data or sum of squared differences. Their calibration results revealed that:

- The pothole distress was same as with the default values of HDM-4 for all terrains
- The cracking progression was 77% slower than predicted by default values of HDM-4 for all terrains.
- The ravelling progression was 66%, 73% and 46% slower than as predicted by default values of HDM-4 in plain, rolling and mountainous terrains.
- The rate of edge break was about 39%, 56% slower and 1.65 times faster that was predicted by default values of HDM-4 for plain, rolling and mountainous terrains.

- The rut depth progression was 2.7, 2.17 and 1.5 times faster than predicted by default values of HDM-4 for plain, rolling and mountainous terrains.
- The pothole progression was about 94%, 84% and 94% slower than predicted by default values of HDM-4 for plain, rolling and mountainous terrains.

They also claimed that HDM-4 pavement deterioration models in their study can be used for the optimal maintenance of low volume roads and recommended that these can be used in other parts of India also.

Shah et al. (2012)selected 21 road sections covering major roads of Noida City for Priority analysis. The inventory data included the following details about any selected pavement sections: name of Road, carriageway width, category of road, road geometrics, type of surface, details depicting the history of maintenance and construction of given roads, etc. They collected this data by visual inspection and measurement of pavement sections, and from the construction and maintenance records of the highway division's in-charge of the maintenance. They carried out theroad traffic volume surveys for a continuous period of 72 hours on 21 roads covering all categories of vehicles which includes non-motorised traffic and structural evaluation was done by Benkelman beamdeflection method. They also considered crust data and cost data along with the functional evaluation of the pavement sections. They evaluated two methods for priority ranking of road maintenance, i.e. ranking based on subjective rating and ranking which was based on economic indicator.The subjective ranking was done using maintenance priority index which is a function of traffic volume factor, road condition index, drainage factor and special factor.The second ranking method was based on economic indicator in which NPV/Cost ratio was calculated for each pavement section using the HDM-4 software.They concluded that out of 21sections, there were inconsistencies in ranking for seven sections while for other sections ranking was comparable and the success for the rest of 67% road sections generated adequate confidence on the MPI-based simplified approach.

Amin and Amador (2013)provided a multi-criteria pavement management system for rural road network of Bangladesh. They discussed the current practices of rural road maintenance which were based on road parameters, condition and cost parameter for Gazipur district. They proposed a model on the basis of mechanistic modelling of roughness progression of pavement surface (Pavement Performance modelling). The model estimated the functional hierarchy on the basis of population thresholds of various functions in the rural area of Bangladesh. Their study applied the Reed Muench method (Haggett and Gunecwardena1964) to calculate the Population threshold. Roughness Index was also modelled on the basis of equivalent single axle load of heavy load axles for certain time, observed pavement strength (Structural Number Coefficient) and mean environmental exposure (Moisture coefficients). Pavement Condition Index (PCI) found by combining Roughness Index, surface distress index and structural adequacy index (rutting, linear cracking). Rural Priority Indicator (RPI) was calculated on the basis of centrality and hierarchy of rural functions (e.g., health, education, small industries, banks, etc.) using population threshold of that region. They had performed traffic analysis by collecting AADT (annual average daily traffic) on the pavements during design life of 15 years. Then, optimization of pavement management system was done by prioritization of weighted values of Pavement Condition Index (PCI) and RPI of the pavement sections. They claimed that 3 million as the minimum annual maintenance budget by which the Pavement Condition Index (PCI) of the whole road network can be increased to 83%.

Most of the studies include the collection of the time series data of pavement distresses only for 2 consecutive years. To develop the effective PMMS, a time series data of 4 to 5 years needs to be collected for adapting the HDM models to the local conditions by performing highest level of calibration.

2.2.2 Development of PMMS using HDM-4

HDM-4 (Highway Development and Management)modelis a pavement maintenance management tool which acts as a decision making tool for estimating the economic or engineering entities of road investment projects. Calibration factors are used for analysis in the HDM-4 model in case of local conditions to get accurate results for the predication of pavement performance by measuring various pavement distresses like cracking, potholes, ravelling, rutting & roughness. Research work of various authors has been discussed below regarding use of HDM modules for predicting the pavement deterioration for various categories of road.

Aggarwal et al. (2004) developed and calibrated the pavement management system for local conditions and they claimed that this system will assist engineers while maintaining the pavements. They used HDM-4 model for this purpose and taken 10 years (2003-2012) of analysis period. They used 22 sections of national highways. They claimed that to maintain the highway at optimum serviceability level, the sum of 1475.87 million rupees had been required and the available budget was just 60% of the required budget. They also prepared priority ranking list of selected sections. They also concluded in their study that there was not much change in the roughness value if the delay was of any one year, but value will rise 6m/km IRI, if it would be delayed for next two years. This will further give a drastic increase in the VOC for the road users.

Jain et al. (2005)calibrated the HDM-4 pavement deterioration models for a National Highway Network which was located in the Uttar Pradesh and Uttaranchal states of India. The data was collected for potholing, ravelling, cracking, and roughness. They analyzed, and used for the calibration of HDM-4 pavement deterioration model. For testing the efficiency of the calibrated model, they validated the models so that it can be adapted for predicting distress and development of the strategies used in maintenance management for the Indian National Highway Network. They monitored and measured the performancesections for a continuous period of 3 to 5 years. This gave way to the pavement performance prediction models for the major modes involved in distress, which includes cracking, potholes,ravelling, and roughness which were the most significant from the view point of road maintenance and road user cost considerations. In their study, the pavement deterioration model relationships were derived on the basis of large number of sections viz. 145 pavement sections located along state highways and national highways in the Indian states of Rajasthan (47 sections), Gujarat (44 sections), Uttar Pradesh (37 sections) and Haryana (17 sections). Four types of distress progression models were validated which used a percentage variable and regression coefficient, included:

• Cracking progression model;

• Ravelling progression model;

• Pothole progression model; and

• Roughness progression model.

They claimed that their study gave the HDM-4 deterioration models which were calibrated for the Indian National Highway Network, could be used for other developing countries as well having similar soil types, traffic characteristics, climatic conditions, pavement compositionand terrain type.

Soo-Hung et al. (2008) collected the data of continuous 4 years of survey work and data included the traffic volume, the maintenance results and the section for which maintenance was required; supplementation and upgradation the DB; and selected the survey section considering the capacity of test devices. They selected the test analysis sections from the survey sections by considering thetraffic volume, the road surface test result, and maintenance history, and by excluding those sections which had good road surface, also the sections having low traffic volume and those sections which were maintained long time ago. They had used Falling Weight Deflectometer (FWD) and Ground Penetrating Radar(GPR) to evaluate the structural state for homogeneous road sections. In the some road sections, cores were sampled from the fields to measure the depth of rutting. The average value of damage element came out to be nearly 11% for crack, 5.3 for MCIand approx.2.5 mm/km for longitudinal roughness. The maintenance method was then selected by them on the basis of the field test result and in overseas cases was fixed through consultation with the experts. The maintenance priority was further determined by economic efficiency test on the sections leaving behind the preferred maintenance sections and the daily maintenance sections.The maintenance priority index was determined on the basis of the difference in cost for 5 years of analysis period in between when the maintenance will be performed in the next year and when it will not be performed (Net Present Value (NPV) considering discount rate 7%). The HDM-4 program developed by the World Road Bank was also used in this analysis work. It was affirmed that early damage occurs in the sections or cross sections where large number of heavy vehicles pass. They compared the results and the comparison of before and after PMS revealedsignificant improved pavement state and reduction in maintenance cost, despite of substantial increase in traffic volume.

Khan et al. (2010)carried out work to improve maintenance standards of road network in Bangladesh so as to maintain road network efficiently. They divided the whole area into 48 groups. Road inventory data, condition data, maintenance strategies with their unit cost were inputted into HDM-4 software and strategy analysis was performed. They also calibrated and validated HDM-4 model for Bangladesh condition before use. They had taken different intervention criteria for each road group depending upon their classification for maintenance strategies. NPV/cost ratio was considered for each road section. They concluded that maintenance strategy which provides higher ratio of NPV/ cost value was selected for that road section.

Rose et al. (2010) developed and calibrated pavement performance models using HDM-4 for rural roads. The data had collected from 20 rural road sections in Kerala, India. Models had been developed for ravelling progression, pothole progression and roughness progression.

They also validated and calibrated the developed HDM-4 models. They also gave the following equations for:

Ravelling Initiation Model:

$$AGEVIN = -0.41 + CQ^{0.69} + 0.5\, DR^{12.29}$$

Ravelling Progression Model:

$$RV_t/T = (RV_i * PAGE)^{0.55} + CQ^{-2.168} + PAGE^{0.637}$$

Pothole Progression Model:

$$PH_t/T = 1.596 + PH_i^{0.9373} + RV_i^{0.398} - 2.086 * (MSN * CQ) + (THBM * PAGE)^{0.097}$$

Roughness Progression Model:

$$RG_t/T = (CQ * RV_i)^{-0.657} - 2.019 * MSN^{-0.733} + (RG_i * t)^{-1.03} + 0.058 * PH_i * PAGE$$

where, RV_t/T = the rate of ravelling progression, T = the time interval in years, RV_i = initial ravelling, %, CQ = the construction quality, PAGE = the Pavement Age since Last Renewal, years, DR = the drainage rating, PH_t/ T = the rate of pothole progression, PH_i = the initial pothole area, RV_i =initial ravelling, m^2, MSN = modified structural number, THBM = the % reduction in thickness provided from design thickness, RG_i = initial roughness. They also reported that:

- The rate of progression for ravelling would be 3.46% for good quality roads and 16.06% for poor quality per year.
- The pothole progression should be 0% for good roads and it could be 4.36% for poor roads for first year.
- For good quality roads, the roughness progression could be at a rate of 0.5%and for poor roads, it could be 2.07% for first year.
- The calibration factors were 0.50, 0.82, 0.72 and 0.70 for ravelling, pothole, roughness age environment and roughness progression, respectively.
- The rate of ravelling, pothole and roughness progression were 33%, 11.4% and 0.9%, respectively, which was lesser than the default values of HDM-4.

Jain et al. (2012) compared the scheduled and condition responsive maintenance strategies using flexible pavement sections flexible pavement sections of National Highway from Ghaziabad ,NH-24 (Total length=40 kms). They divided the pavement into 8 sections of 5 kms length of each). They had selected sections based on maximum NPV/Cost ratio. An effort had been made by them to show the optimum utilisation of maintenance funds based upon this comparison. They had used:

- pavement condition data (such as basic road details, geometrics, pavement history and pavement conditions),
- traffic data, pavement age; and
- Deflection data (light weight & falling weight deflectometer and deflection data) as input.

They had concluded that the condition responsive maintenance is much better than scheduled maintenance over the design life of 10 years during economics analysis of this study. They also suggested that 40mm thick overlay as an optimum M&R alternative for the selected sections.

Jorge et al. (2012) proposed pavement management optimum system which was claimed by them that could provide a good solution to the pavement maintenance management problem involving periodic and routine maintenance. Their objective was:

- to minimise construction cost,
- to minimise maintenance cost,
- to minimise user and residual cost.

For this, they considered number of years, discount rate, area and volumes, performance, structural and functional quality, annual budgets and minimum quality level as input parameters. They also applied some of the constraints on the developed models like verifying the minimum quality levels, using only the M&R actions defined by the infrastructure managers, not exceeding the available budget and not exceeding the maximum number of M&R actions during the planning period. This study was conducted on the Portugal and reported the cost, structural and functional quality of Portugal. They had used the same optimisation system as in AASHTO pavement performance model and substituted by HDM-4 models to take into account recent Portuguese legislation. They claimed that it is very valuable addition to the road engineer's toolbox.

Han and Kobayashi (2012)suggested 'Stepwise DirectionalCustomization Approach' (SDCA) which was defined as 'A formal (or the best) direction of development of PMS considering user's current and desired PMS capabilities level'. The basic development strategy, the SDCA, have three important benefits which includes:

- assessment of the current PMS situation by using standardized index,
- show the best development scheme in accordance to any PMS situation, and
- acquire every country on track towards the development of PMS (i.e., toward having compatibility with others).

They defined 2 phases of PMS which includes 5 general stages and 2 mature stages of SDCA, general stages as A, B, C, D and E and mature stages are F and G. They classified the general functions by PMS capability levels. They created links with PMS framework and data requirements by determining suitable PMS capability levels. They also classified general functions into further 6 categories according to the main roles of PMS and importance level. They also suggested 4 pre-defined datasets supporting each PMS capability level and further, provided the 'General pavement condition indices' for bituminous pavement. They also explained the considerations for PMS development at functional levels,which included PMS cycle, data definition, database, economic analysis, deterioration models and heterogeneous factors. They also provided the brief summary of the PMS Development (Improvement) Plans of Korea, Vietnam and Japan.

Jain et al. (2013) developed an optimum maintenance and rehabilitation strategy using HDM-4 on the multilane highways from northern region of India. The implementation criteria had been selected according to the Indian guidelines on pavement maintenance. Input data had been collected and entered in the form of:

- road network data,
- vehicle fleet data and
- work standards

They considered five factors for evaluation also, that were, ravelling, potholes, cracks, rutting and patching. They proposed five M&R alternative strategies. Economic analysis had been done for NH-24 for 8 road sections. They concluded that alternative 3 (i.e., resealing and overlay, 25mm SDBC reseal + overlay of 40mm BC + IRI $\geq$ 2.8 m/km) for Noida-Greater Noida Expressway and alternative 2 (i.e., Thick overlay, overlay of 40mm BC, IRI $\geq$ 2.8 m/km) was considered best for NH- 24 road sections.

Girimath et al. (2014) developed model for pavement prediction model using HDM-4. They had selected 13 major category roads of Karnataka and measured the data in terms of cracking, patches and potholes, ravelling, rutting, edge breaking and the cost data for maintenance were collected from Highway department, Bangalore. Their methodology involved five stages. They have done the selection of urban road network and selected 12 road sections and collected data like history of road maintenance, maintenance strategies existing, the cost data for maintenance of road network and routine maintenance details in second step. Pavement condition evaluations has been done in third stage *i.e.*, measurement of distresses like potholes, patching, ravelling, surface cracking *etc*. HDM-4 had been implemented in Fourth stage to analyse the roadway network at Project level and network level. The prioritization of road network based on economic analysis *i.e.*, NPV/CAP ratio was the final stage. They conducted road condition survey was done for each road sections. They carried out Project level pavement analysis using HDM-4 software with various Maintenance and Rehabilitation alternatives and generated the Pavement deterioration and M&R works reports. They reported in their study that:

- 40 mm BC came out as optimum for the maintenance treatment of urban roads.
- HDM-4 could be used successfully for economic analysis.
- The renewing of roads should be done on average time period of 2 years and could vary between 2-10 years for the individual roads.

Deori et al. (2016) carried out a study to calculate calibration of inbuilt distress models of Highway Development and Management (HDM-4) tool for Indian conditions and then Validation of calibration factors through similar pavement layer composition with different traffic scenario for different environmental and climatic zones of India by considering 23 sections on a National Highway Development Programme Road project and Determination of realistic and logical calibration factors for different inbuilt distress models in HDM-4 where modified bituminous mixes are used in surface course and they concluded that the selected test sections in this study cover almost entire country from east to west and north to south including the variations in climatic and environmental conditions, traffic loading and the prevailing pavement layer compositions and can be adopted for other high-speed corridors, viz. national highways of the country based on climatic conditions.

Cutura et al. (2016) presented application of HDM-4 model for local road network in Herzegovina- Neretva canton of Bosnia and Herzegovina. They had selected 13 road sections with traffic varies from 27 - 12375 VPD. They also reported the average roughness index of network was 4.49 m/km. They defined maintenance strategies based on traffic and roughness. The intervention costs that are used is calculated on the basis of market prices. They defined the priorities of road networks with the ratio of NPV/CAP. They compared budget with the help of HDM-4 which showed budget sanctioned was not sufficient and concluded that NPV was negative and internal rate of return obtained for maintenance alternates were below routine alternates of treatment for pavement section. They performed first phase using unconstrained budget. The total value of the needed road works amounts to 21.16million, out of which 20.63 million was the cost during first year. They also implemented the cost budgets for annual allocation of 2-3 million kms. They claimed that this type of study would assists local road agencies to manage their road networks and define road works priorities in developing countries.

Shah et al.(2016)aimed to maximising the NPV and minimisation of the cost to achieve target international roughness index and carried out analysis of 21 urban pavement sections. They calculated traffic for motorized and Non-motorized traffic along with characteristics deflection. They reported the variability in roughness 3.21 - 5.65 IRI m/km, deflection 1.287mm - 2.873 mm and considered roughness as primary controlling factor for activating provisions of overlays and strengthening of the pavement. They revealed that economic analysis for design period of 10 years and they had done work to maximize NPV for 5 sections of urban road with thin overlay of 25mm SDBC, for 2 sections thin overlay of 40mm BC and for remaining sections of the road network with 50 mm DBM and 40 mm BC. They revealed that NPV and minimum cost for targeted IRI was considered as best alternative. They concluded that:

- When the criterion of maximising NPV had been used, then the best possible treatment applied on the road network depending on the level of maintenance.
- When the criterion of minimising costs for target IRI was consider, the ' strengthen with 50mm DBM + 40mm BC' came out as the best investment alternative because it can keep the entire road network at an acceptable condition.

Prachallaja et al. (2016)developed a model for urban road section of Hyderabad City of 39.9 km total length of road. They observed minimum and maximum range of various pavement performance indicators which were cracking 2.3% - 16.6%, potholes 1- 6 numbers, IRI 2.08 m/km -5.41 m/km and deflection 1mm - 1.82 mm. They reported the conclusions based on the visual inspections that maintenance of the roads was not on time. They stated that quality of material was not up to the mark and this lead to high maintenance cost for some pavement sections. Drainage facility of water caused the damage to the pavements badly. Traffic growth rates were very high, because of this the width of all the load sections varied alot.

They concluded that prioritization leads to check of various sections with help of OPCI which required immediate M&R.

Mane et al. (2016)carried out a study of prioritising of road stretches according to severity and ranking in Jhunjhunu district of Rajasthan and this district is sub-divided into 8 blocks Pradhan Mantri Gram Sadak Yozna(PMGSY). The road section comprised total length comprises of 18 km length of rural roads which consisted 6 blocks and 180 sections. The road was two lane undivided asphalt pavement and distress were inspected visually for each 100 m section and reported he Potholes depth varied from 1cm-5cm, rutting depth from 0 - 1.6 cm, cracking width from 1 - 2 cm. For priority of roads, team of four pavement engineers and researchers were employed to rate individual distress by comparing with other distresses on numeric scale of 1-5. Rank 1 represented as the most severe distress and should be repaired with high priority and Rank 5 represented as least severe distress and should not need any repair. They considered above parameters for AHP to prioritize the pavement sections for maintenance during limited budget allocation.

Most of the authors work is regarding development of HDM-4 is related to a high speed corridor roads like National Highways, by calibrating the distress models of HDM-4 by a time series data of pavement distresses. Very few papers regarding the development & detailed calibration of maintenance management system for urban roads in India.

2.2.2 Development of PMMS using soft computing techniques

Fwa et al. (2000) developed a genetic algorithm to solve pavement maintenance problems. They had used Pareto frontier and rank-based fitness evaluation. The objective of their study was to: 1) minimisation of the total maintenance cost 2) maximisation of overall network pavement conditions 3) maximisation of maintenance work production. For this, they had considered the following architecture:

- Initial Pool Random Generation
- Parent Pool Size 200
- Offspring Pool Size 160
- Mutation Rate 10%
- Stopping Criterion 500 iteration
- Fitness Rank based

The developed algorithm demonstrated the two- and three- objective optimisation analysis with the help of example and also concluded that the improved pavement condition could be achieved in the three- objective solutions. The first two- objective functions are slightly compromised as compared to the two-objective solutions.

Gupta et al. (2011) developed ANN and statistical models for the prediction of low volume road performance. They had collected data continuously 2 years from the pavements of Uttarakhand and Uttar Pradesh, India. They measured the structural and functional response from 18 sections of low volume pavements. From which, 13 sections were in plains and 5 sections were in hilly areas. The sections were divided on the basis of present traffic ($\geq$ 30 CVPD &$\leq$ 30 CVPD), CBR of subgrade ($\geq$ 5 &$\leq$ 5) and age ($\geq$ 3 &$\leq$ 3). They had developed 7 models for deflection prediction using linear and non-linear models and 6 models for ride quality prediction models using regression analysis. The results of the study yielded that non-linear models worked better than linear models and when compared non-linear models with ANN models, the performance of ANN came out best in terms of R^2. They also reported that age and traffic are the most important parameters or the performance indicators for low volume roads.

Chandra et al. (2013) developed linear and non-linear regression models for roughness and distress parameters. They also developed ANN for the same data set using sample set of 510 tuples. The model was developed by considering architecture of 5 input neurons, 15 hidden neurons and 1 output neuron. The data was collected from NH-49, NH-205, NH-6, NH-15 using Network Survey Vehicle (NSV). They evaluated these models using Mean Absolute Error (MAE), Root Mean Square Error (RMSE) and Mean Absolute Relative Error (MARE) as fitness function. They reported the values of MAE, RMSE and MARE for multiple linear regression 0.467, 0.55 and 16%, respectively and for non-linear regression, the values of MAE, RMSE and MARE were 0.435, 0.515 and 14.6%, respectively. They claimed that best values of MAE, RMSE and MARE were 0.387, 0.469 and 12.6%, respectively, in case of ANN. They revealed that ANN model is better than linear and non-linear regression models as these models were unable to perform when the number of parameters was increased because of their poor mapping between independent and dependent parameters. On the other hand ANN is a distribution free model which does not consider the linear and non-linear nature of the parameters.

Katkar et al. (2013) developed an application of Markov models for PMMS. Road condition data was collected on 20 pavement sections. They claimed that Markov approach helps to develop a decision support system for pavementmaintenance in any state at any given point.

Their methodology included analysis of historical data, with passage of time pavement deteriorates andtransition probability matrix is used for estimating future performance and they had also used Poisson‘s distribution for formulating one step transition matrix and calculating successive transition matrices for predicting future performance of pavement. They concluded that their study developed a quantitative approach in the form of mathematical model to represent pavement deterioration models based upon Markovian process.

Sandra et al. (2013) developed relationship between roughness and other pavement distress parameters such as cracking, potholes, patching, rutting and ravelling. The data was collected over 39.5 km length of road of different functional classes such as National Highways, State Highways and Major District Roads in Rajasthan, India. They developed multiple linear regression models to find relation between IRI and other parameters using SPSS. The equation had given by them:

$$IRI\left(\frac{m}{km}\right) = 0.0143 * RL + 0.0216 * RM + 0.0345 * RH + 0.0303 * PAL + 0.0418 * PAM + 0.0432 * PAH + 0.111 * PL + 0.151 * PM + 0.178 * PH + 0.0103 * CL + 0.0018 * RUL + 0.0023 * RUM + 0.0034 * RUH$$

where, IRI = IRI due to distresses only in m/km; RL = low severity ravelling in % area; RM = medium severity ravelling in % area; RH = high severity ravelling in % area; PAL = low severity patching in % area; PAM = medium severity patching in % area; PAH = high severity patching in % area; PL = low severity potholes in % of area; PM = medium severity potholes in % area; PH = high severity potholes in % area; CL = low severity cracking in % of area; CM = medium severity cracking in % of area; CH = high severity cracking in % of area; RUL = low severity rutting in meters per km; RUM = medium severity rutting in meters per km; RUH = high severity rutting in meters per km. They had reported 0.986 as the value of R^2.

Al-Zoubi et al. (2015) developed a model for populating missing performance data using statistical approach and applied the technique to model free replacement and model distribution. They used linear interpolation based on nearby distresses, regression models and cubic spline and conducted study over Texas using TxDOT database which divided them into 25 districts. They revealed that efficiency differ for one missing data to three missing data point *i.e.* one point data showed 34% accuracy, two point data showed 12% accuracy and

20% accuracy for three point missing data and suggested that these techniques helped to populate missing data leads to a significant improvement in predicting distress score.

Prakasan et al.(2015) conducted a study for 21 urban road sections of Noida City. Their methodology adopted for study was the field data collection considering the cracking, deflection and roughness of the road surfaces. They compared the variation for direct assessment and analytical hierarchy process by using Priority Index (PI) of road class, riding quality, drainage and Structural Adequacy (SA). They concluded that the riding quality had highest weightage of 0.158 in priority ranking process followed by Structural adequacy 0.141, safety condition 0.128, traffic volume 0.115, drainage condition 0.105 and road class 0.088 using Analytic Hierarchy Process (AHP) and their results by using direct assessment tools shows riding quality was 0.178, PSR 0.159, SA 0.124, safety condition 0.123, traffic volume 0.118 and road class 0.108. They compared on priority basis and concluded that outcome was less précised in AHP due to fixed scale in some cases.

Most of the published papers used the concept of neural networks, Markov approach and Genetic algorithms to predict the pavement distresses. Application of techniques like Genetic Programming has been lacking to predict the pavement deterioration for the urban roads in India.

2.2.4 Application of GIS for development of PMMS

Niaraki et al. (2011) worked on auto-updating of GIS Dynamic Segmentation (DS) technique to carry out PMMS for Tehran city of Iraq. They proposed approach for Road Maintenance and Transportation Organization (RMTO) on road network of Tehran city. Automatic approach for updating old segment require identifying the type of changes from old to new segment and changed type was considered as spatial relationship between old and new segment on the route. They have considered variability in automatic updating was from 0.2 – 0.4 seconds whereas in manual upgradation it varied from 15 – 62 seconds. They revealed that real time segments need to be updated by new segments as early as possible for efficient data base.

Rusu et al.(2015)proposeda platform for pavement management and pavement maintenance and integrate new technologies in order to design and implement an automated visual road inspection system. They divided the system into three parts: general information, Image acquisition and processing, management and maintenance module. These modules were linked with image database and pavement application database. Image database stored all the images and videos and pavement application database stored project schedules, materials and resource data. They conducted visual inspection so that update can be provided by GIS with least cost and prepared a model based on inspection, material and source database.They claimed that this system can help for traffic speed pavement distress monitoring and analysis and can be installed on non-specialized vehicles. Their approach suggested a pavement analysis using ArcGIS, a GIS solution on vehicle, camera and other sensors. They concluded that this all lead to decision making of cost, prediction and risk involved which was incorporated with help of software which linked management and maintenance module in different phase of analysis.

Bardeesi et al. (2015) evaluated the road conditions by collected the data from the Deputy Ministry for Technical affairs, the ministry of Municipal and Rural affairs, Saudi Arabia. They divided the total area into 5 regions according to climate conditions and 14 Emirates, 160 municipalities. They tested 1260 samples of road sections available. They had conducted pavement condition assessment based on the estimation of urban distress index. The value of urban distress index values from 0-100. They investigated various tools of environment impact of the product. The software used by them for the collection of data were ArcGIS, Oracle 10g, Visual Basic 6.0, and MS-Access. Their work was setting up a framework for life cycle assessment of products in abundance or on verge of extinction. The Ministry also used tools like MOVES2010, NONROAD and PaLATEW for assessing single or multiple types of pollutants.

2.3 GAPS IN PRESENT STUDIES

From the literature review on various components of PMMS following gaps have been identified:

1. It is found that a comprehensive PMMS needs to be developed which includes all the components and can be efficiently implemented by urban development authorities.
2. Advance mechanism and automated data collection equipments should be used to have an accurate and faster data collection for an efficient PMMS.
3. Highest Level Calibration of Road Deterioration and Maintenance Effects (RDME) models of HDM-4 for urban roads has not been incorporated which has to be considered for an effective urban PMMS for India which will have great practical application in managing road infrastructure of India.

4. Soft Computing techniques such as genetic programming have been lacking for the development of pavement deterioration models for urban roads under local condition.
5. GIS application for PMMS needs to be implemented for the selected road network so that the database related to road conditions can be continuously updated and the developed pavement maintenance management system can be more effectively implemented by the highway authorities.

2.4 SUMMARY

Pavement Maintenance Management System has been defined in several ways by different organizations and pavement management practitioners. There are some milestones that can be considered to have advanced the evolution process of pavement management systems over last three decades. Presently, many highway development authorities in developed countries are using a systematic and scientific methods to determine the pavement condition throughout the design life of the pavements and scheduledthe maintenance activities in response to real situation by providing suitable intervention criteria's so as to preserve the highway infrastructure to the desired serviceability conditions within the budget constraints. In many of the developing countries, PMMS is in various phases of working process with diversified approaches as per the respective needs and problems of each country. The latest technologies like GIS, ANN, GA *etc*. are being used to enhance the pavement management process. Various pavement performance prediction tools have been developed by various highway agencies across the world to schedule the maintenance activities, but they are not accepted throughout the world. However, one possible exception is HDM-4. In view of its international recognition and vast acceptability, especially in developing countries, HDM-4 has been recommended to be the most suitable PMMS software for developing pavement maintenance management system as a decision making tool for an identified road network by properly calibrating the various pavement deterioration models according to the local conditions especially for the small to medium size cities in India where there is a major constrained on the maintenance budgets.

CHAPTER 3

METHODOLOGY AND DATA COLLECTION

3.1 GENERAL

This chapter explains data collection and methodology used for the development of Pavement Maintenance Management System (PMMS). Methodology for developing a PMMS includes all the modules & processes involved in the systematic & scientific development and implementation of PMMS. In this chapter, methodology and data base collection for developing the maintenance management system has been discussed.

3.2 METHODOLOGY FOR DEVELOPING PMMS

An efficient PMMS depends on accuracy, integrity, reliability and the most important completeness of database. For successful analysis, the database should be organized in such a manner that data could be retrieved easily.

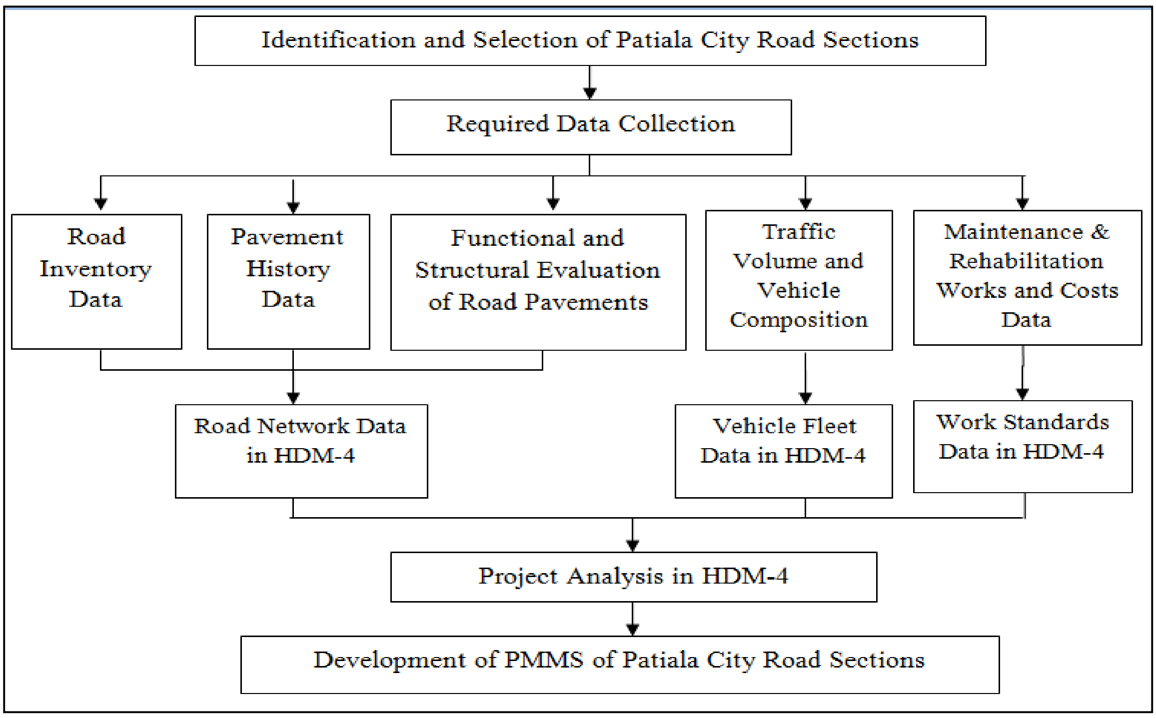


Fig. 3.1: Methodology to develop PMMS for Patiala Roads

The most important data for PMMS is about the inventory data of road section, pavement performance data, pavement history, geometry and cost related description of road. A detailed description of the collected data, procedure of data collection and equipments used for the same are given in the subsequent sections. Methodology for developing PMMS of Patiala city road sections is shown in Fig. 3.1 with the help of flow chart (Jyoti Mandhani & Tanuj Chopra, 2016).

3.2.1 Identification and Selection of Patiala City Road Sections

In this research work, Patiala city road network has been identified and sixteen road sections have been selected for developing PMMS. Fig. 3.2 shows map of Patiala Urban Road Network.

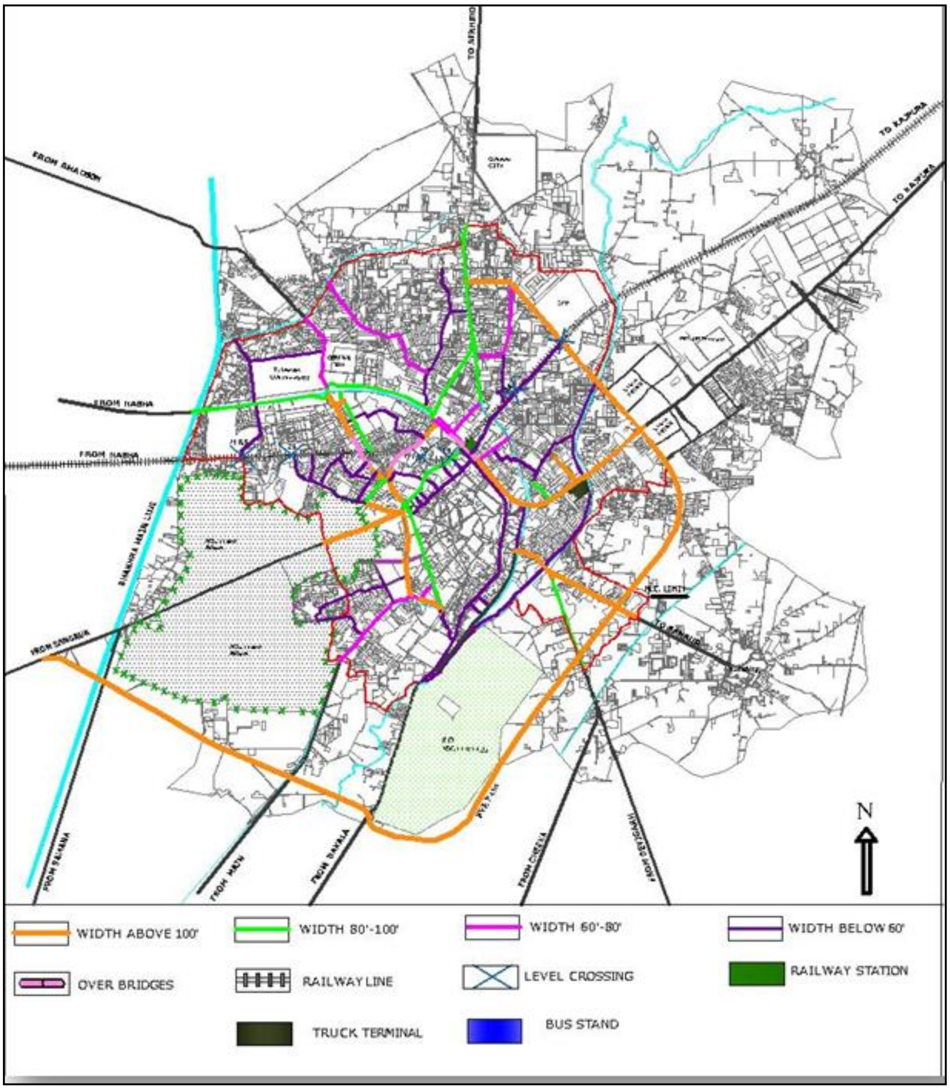


Fig. 3.2: Map of Urban Road Network of Patiala (Punjab, India)

The selected 16 road sections are major sub arterial & collector roads of Patiala city. All the sixteen road sections selected for developing PMMS have been assigned a unique 'Section ID' as given in Table 3.1 and also shown in Fig. 3.3.

Table 3.1: Inventory Data of Selected Road Sections

Section ID	Name of Road	Length (in kilometer)	Width of Carriage way (in meter)	Drainage Condition
UR01	Thapar Univ. - Bhadson Road	0.80	6.80	Fair
UR02	Thapar Univ. - Bhupindra Road	1.05	7.30	Fair
UR03	Thapar Univ. - Gurdwara Sahib (Passey Road)	2.50	7.50	Good
UR04	Passey Road - Civil Line (Ghuman Road)	1.00	7.20	Very Poor
UR05	Gurudwara Sahib Chowk - Sirhind Road	2.25	7.00	Good
UR06	Leela Bhawan Chowk – Cantonment	0.70	11.50	Good
UR07	Gurdwara Sahib Chowk - Bus Stand Road	0.90	7.50	Poor
UR08	Thikriwala Chowk - Sangrur Road	1.00	7.50	Good
UR09	Thikriwala Chowk - Badungar Road	0.80	11.80	Fair
UR010	Bus Stand Chowk - Gurbax Colony	2.10	6.0	Poor
UR011	Fountain Chowk - Leela Bhawan	0.70	12.5	Good
UR012	Fountain Chowk - Lower Mall	2.25	7.5	Fair
UR013	ThaparUniv. - Gurudwara Sahib	2.25	7.30	Fair
UR014	Leela Bhawan Chowk- 22 No bridge	2.10	7.50	Good

UR015	Leela Bhawan Chowk-Gurdwara Sahib (Rajbaha Road)	1.46	10.0	Fair
UR016	Leela Bhawan Chowk-Baradari Garden	1.10	6.40	Good

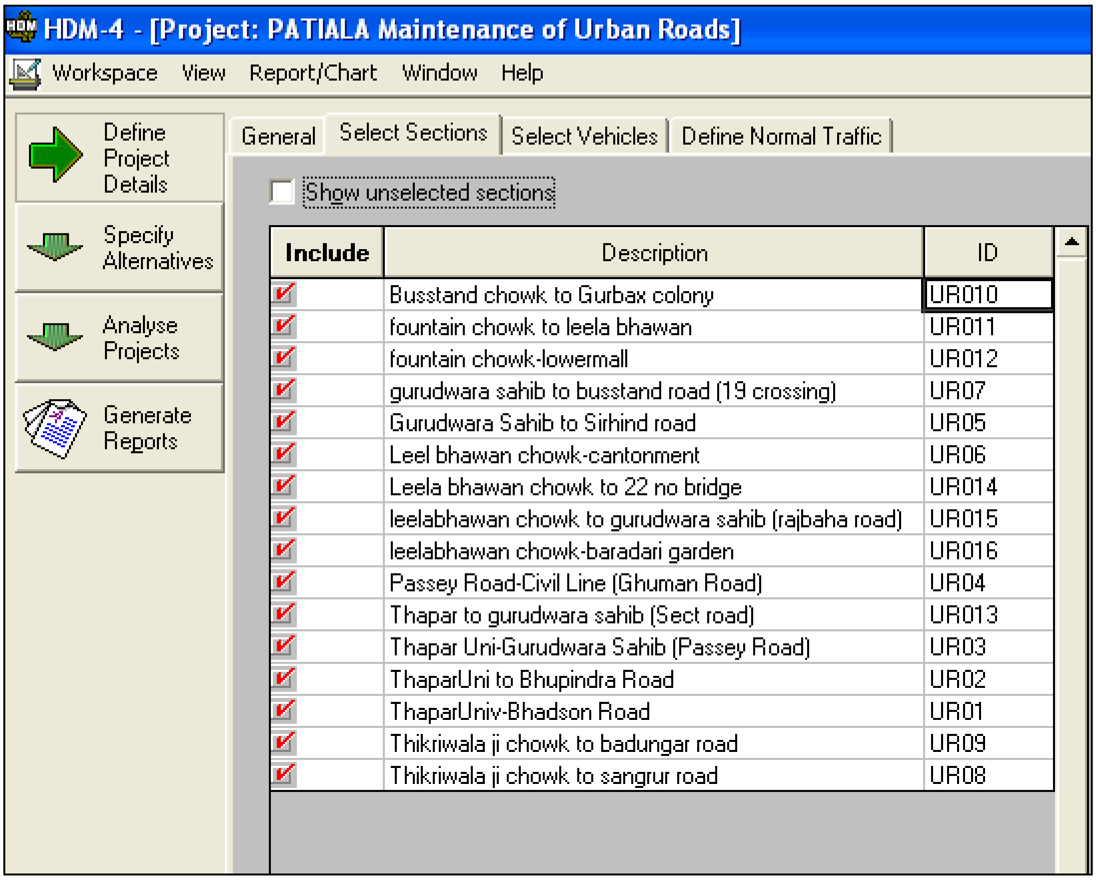


Fig. 3.3: Selected Urban Road Network of Patiala City

3.3DETAILS OF DATA REQUIRED

For developing an efficient PMMS, data is to be collected for the entire selected road network and is collected in the form and units as required by the HDM-4 software for running the various modules of HDM-4 for developing the maintenance management system.

Data collection required has been divided into four categories, as required by HDM-4, which are as follows:

- Road Network Data
- Vehicle Fleet Data
- Maintenance and Rehabilitation (M&R)Works Data
- Costs Data

Road Network data refer to base line road inventory data, pavement crust and construction year data and pavement roughness, deflection & other distress data *etc*. Vehicle fleet data include representation of vehicles with their basic characteristics. Maintenance & Rehabilitation Work's data refer to assigning various maintenance activities for the road sections as per the existing departmental practices. Costs data include road user cost data and cost of various maintenance and improvement works. Detailed methodology of data collection and IRC codal provisions & procedures for collecting the data using various equipments such as Benkelman beam, Roughometer etc. have been discussed in further sections.

3.4 ROAD NETWORK DATA COLLECTION

3.4.1 General

As per the requirements of HDM-4, the road network data collection has been carried out for all the sixteen Patiala road sections. The road network data collection has been divided into four basic components as required in HDM-4

- Road Inventory Data
- Traffic Volume Data
- Pavement History Data
- Pavement Functional and Structural Evaluation Data

In order to adapt HDM-4 for use in the present study, the various road network elements have been defined as given below (Aggarwal 2004):

- ***Speed flow type***

  In the study, the speed flow type on selected road sections varied from 'Two Lane Standard' to 'Four Lane Standard' as per the basic inventory details of the road sections.
- ***Climate zone***

  Climate zone of 'North India Plain', has been defined on the basis of mean annual temperature and mean annual precipitation characteristics for the 16 road sections defining the Mean annual temperature of 24.5 ˚C and mean annual precipitation of 254 mm for Patiala city (source: Climate-Data.org).

3.4.2 Road Inventory Data

The inventory data includes the following details about the selected road sections:

(i) Classification of road

(ii) Length & Width of Section

(iii) Visual Condition of carriageway and drainage aspects

The above data has been collected from visual inspection of the pavement sections, as well as from the Municipal Corporation, Patiala. The details of road inventory data are presented in Table 3.1(Section 3.2).

Drainage Condition Data: Drainage condition has been considered as per the HMD-4 manual guidelines. Drainage factor based upon drainage time and quality has been used to calculate the pavement strength and even the roughness progression environment coefficient in HDM-4 module is dependent upon this drainage factor. Subjective assessment is based on the large sample size sample of minimum 10 people for each road section. The drainage coefficient value effects the strength of the pavement and for the calculation of the SNP with respect to the pavement crust, drainage factors has been considered Data regarding side drainage condition on the sixteen Patiala road sections has been collected on the basis of visual inspection and local public opinion. Drainage condition for the section is classified as shown in Table 3.2. Figs. 3.4-3.6 show the drainage condition on different road sections (Jyoti Mandhani & Tanuj Chopra, 2016).

Table 3.2: Relationship between Drainage Time and Drainage Quality

Drainage Quality	Excellent	Good	Fair	Poor	Very Poor
Time to drain off the water from carriageway	2 hours	12 hours	1 day	3 day	> 3 days

Fig. 3.4: Choked Drain on Road Section UR01

Fig. 3.5: Water on Shoulder side of Road Section UR02

Fig. 3.6: Water on carriageway of Road Section UR04

3.4.3 Traffic Volume Data

In the present study, Traffic volume data has been collected from Local Government Departments of Patiala & PUDA masterplan report. In HDM-4 model, Traffic data is entered in the form of Annual Average Daily Traffic (AADT) and PCSE unit as required in HDM-4. As per HDM-4 manual, PCSE (Passenger Car Space Equivalent) is termed as the differences in space occupied by each vehicle based on its size (length of vehicle) as compared with that of standard vehicle (car). AADT for each section were calculated by summing up the products of number of individual vehicle and its PCSE factor. Table 3.3 shows the traffic volume per hour of each road section.

Table 3.3: Traffic Volume Data of Road Sections

Section ID	Cycle	Rickshaw/Rehri	Scooter/M-Cycle	Car/ Jeep/ Auto	Bus/Truck/ Tractor/ Trolly	Cart	Total
UR01	198	118	350	371	112	22	1171
	16.9	**10**	**30**	**31.7**	**9.6**	**1.8**	**100**
UR02	234	73	552	285	33	5	1182
	19.8	**6.2**	**46.7**	**24.1**	**2.8**	**0.4**	**100**
UR03	152	141	341	285	78	5	1002
	15.2	**14.07**	**34.03**	**28.44**	**7.8**	**0.5**	**100**
UR04	108	18	251	115	10	3	505
	21.7	**3.5**	**49.7**	**22.7**	**1.9**	**0.6**	**100**
UR05	110	69	272	317	120	12	900
	12.2	**7.66**	**30.2**	**35.2**	**13.3**	**1.44**	**100**
UR06	251	180	547	265	33	4	1280
	20	**14**	**42**	**21**	**2.6**	**0.4**	**100**
UR07	267	201	584	535	129	15	1731
	15.4	**11.6**	**33.7**	**31**	**7.4**	**0.9**	**100**
UR08	191	207	865	927	164	3	2357
	8.1	**8.8**	**36.71**	**39.34**	**6.93**	**0.12**	**100**
UR09	171	99	470	338	88	2	1168
	15	**8.5**	**40**	**29**	**7.5**	**0.1**	**100**
UR010	407	459	1104	65	5	-	2040
	20	**22.5**	**54.1**	**3.2**	**0.2**	**-**	**100**
UR011	583	247	705	864	438	5	2842
	21	**9**	**25**	**29.8**	**15**	**0.2**	**100**
UR012	464	358	722	878	34	12	2468
	19	**14.5**	**29**	**35.6**	**1.4**	**0.5**	**100**
UR013	404	92	548	347	196	5	1592
	25.4	**5.8**	**34.4**	**21.8**	**12.3**	**0.3**	**100**
UR014	554	349	1275	1106	112	8	3404
	16.3	**10.2**	**37.5**	**32.5**	**3.3**	**0.2**	**100**
UR015	381	319	1427	1179	714	20	4040
	9.4	**7.6**	**35.2**	**29.2**	**17.6**	**1**	**100**
UR016	371	180	580	144	2	3	1280
	29	**14**	**45.3**	**11.3**	**0.15**	**0.25**	**100**

3.4.4 Pavement History Data

Pavement data such as type of pavement surface, last construction year, last surfacing and maintenance, any major improvement works such as widening has been collected from PWD and Municipal Corporation of Patiala. The same has been incorporated in HDM-4 for running various modules for developing PMMS.

3.4.5 Structural Evaluation of Pavements

The rebound deflection method of Pavement Evaluation & Overlay design is based on the concept that stretches of flexible pavements that are in service and have been conditioned by traffic, would deform elastically under a wheel load and when the load is removed or is moved forward, the deflected pavement surface would rebound. The Benkelman Beam Deflection (BBD) method is used for evaluating the structural condition of the flexible pavement as per the procedure laid down in IRC: 81-1997. Fig. 3.7 shows the different components of Benkelman Beam apparatus and Figs. 3.8 - 3.10 show the BBD survey under process (Chopra, T, Parida, M, Kwatra, N, Mandhani, J. (2017)

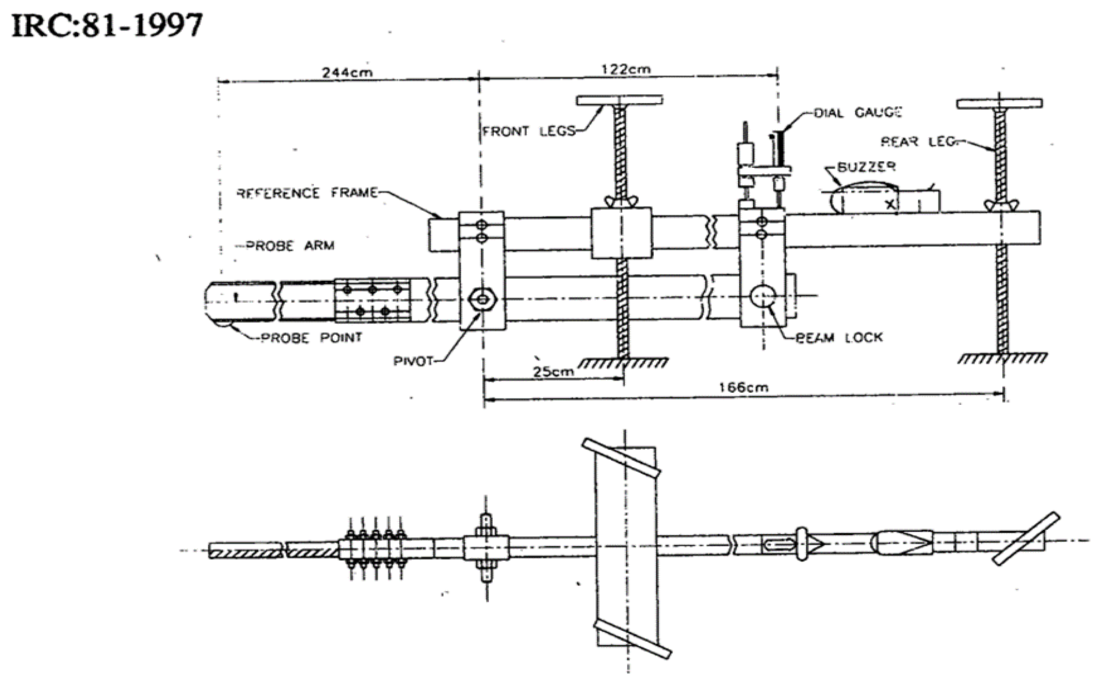


Fig. 3.7: Different Components of Benkelman Beam Apparatus

Fig. 3.8: Placement of Beam Probe in between Rear Tires of Truck

Fig. 3.9: BBD Test in Progress at Chainage 0.200 km, Section UR02

Fig. 3.10: BBD Test as per IRC 81 guidelines

The following data is required for evaluating the pavement deflection:

(i) Truck specifications for conducting the test (IRC: 81 guidelines):

Rear axle weight of the truck = 8170 kg, Tyre pressure = 5.6 kg/cm^2
Spacing between the tyre walls = 30 - 40 mm.

(ii) Temperature data:

The standard temperature for performing the experiment is 35˚C. Since it is not always possible to conduct the test at the standard temperature, a correction factor has to be applied for the deflection. The correction factor is determined by knowing the temperature at the time of testing. Fig. 3.11 shows the actual pavement temperature determination on UR03 (Jyoti Mandhani & Tanuj Chopra, 2016).

The procedure for determining the temperature is as given below.

- A hole has been drilled into the pavement with the help of a mandrel. The depth of the hole has 45 mm and the diameter of the hole is 1.25 cm at the top and 1 cm at the bottom.
- The hole has been filled with glycerol and the temperature has been recorded after 5 minutes with the thermometer (range of temperature between 0 - 100˚ with 1˚ division).
- The temperature readings have been measured for every hour during the survey.

Fig. 3.11: Determination of Actual Pavement Temperature on Road Section UR03

(iii) Soil data:

As per the IRC: 81 guidelines, the deflection measurements using Benkelman beam should be made when the subgrade is at its weakest condition. IRC recommends to conduct BBD survey soon after the monsoon season. But since the reading were taken in November, seasonal variations correction have been applied which will depend upon the type of soil, annual rainfall data and the field moisture content in the subgrade soil.

Calculations for the Characteristic Deflection (D_C):

1. As per IRC 81 guidelines, the test point shall be preselected and marked. For highway pavements, test points shall be located at the distance of 0.6m for lane width less than 3.5m, 0.9 m for lane width of more than 3.5m and 1.5 m for a divided four lane highway from the edge of the pavement.
2. The Characteristic deflections calculated as per IRC 81 for all the road sections is used for measuring the structural adequacy of the pavements by taking the initial, intermediate and final deflections readings of the Benkelman.

- D_0: - Initial reading (obtained when the rate of deformation of pavement is less than 0.025mm per minute)
- D_i: - Intermediate reading (Truck is slowly moved to a distance of 270 cm and stopped and reading obtained when the rate of deformation of pavement is less than 0.025mm per minute)
- D_f: - Final reading (Truck is further driven to 9m & final reading is obtained when the rate of deformation of pavement is less than 0 .025mm per minute)

Overlay Deflection (OD) when $D_i - D_f < 0.025$ mm

$$OD = 2 (D_o - D_f)$$

Overlay Deflection (OD) when $D_i - D_f > 0.025$ mm

$$OD = 2 (D_o - D_f) + 2K (D_i - D_f)$$

Where K = 2.91 **[IRC: 81-1997]**

Temperature & Seasonal corrections have been applied as per IRC 81 guidelines.

Mean deflection, $X_m = \sum$Corrected deflections / n. Here, n is no. of observations

- Standard deviation, $\sigma = \text{sqrt} (\sum(X_i - X_m)^2 / n-1)$
- Characteristic Deflection, $Dc = X_m + 2\sigma$; for NH and SH

$Dc = X_m + \sigma$; for Other Roads

Adjusted Structural Number (SNP) for all the pavement sections has been calculated from the Benkelman deflection readings as per the relationships given by Odoki and Kerali, 2000. Fig. 3.12 and Fig. 3.13 show the progressive variation of BBD and SNP for road sections UR01 to UR016, respectively.

For granular base courses

$$BB_{def} = 6.5 * (SNP)^{-1.6} \quad \textbf{(3.1)}$$

For bituminous base courses

$$BB_{def} = 3.5 * (SNP)^{-1.6} \quad \textbf{(3.2)}$$

3.4.6 Functional Evaluation of Pavements

Surface distress data has been collected for all the road sections of Patiala city from 2012 to 2015. Distresses in terms of cracking, potholes, ravelling, rut depth and roughness has been measured for four progressive years using various equipments for pavement evaluation.

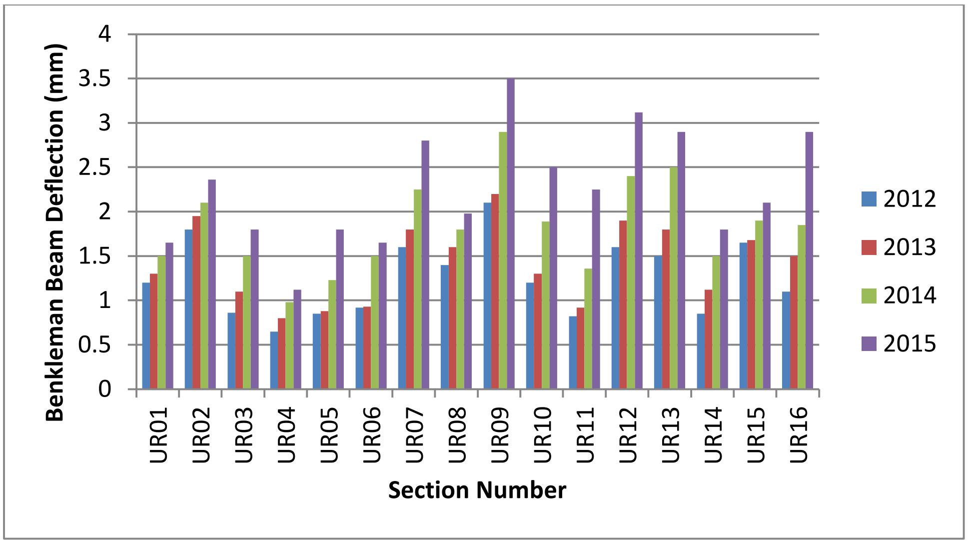


Fig. 3.12: Progressive variation of BBD for Road Sections UR01 to UR016

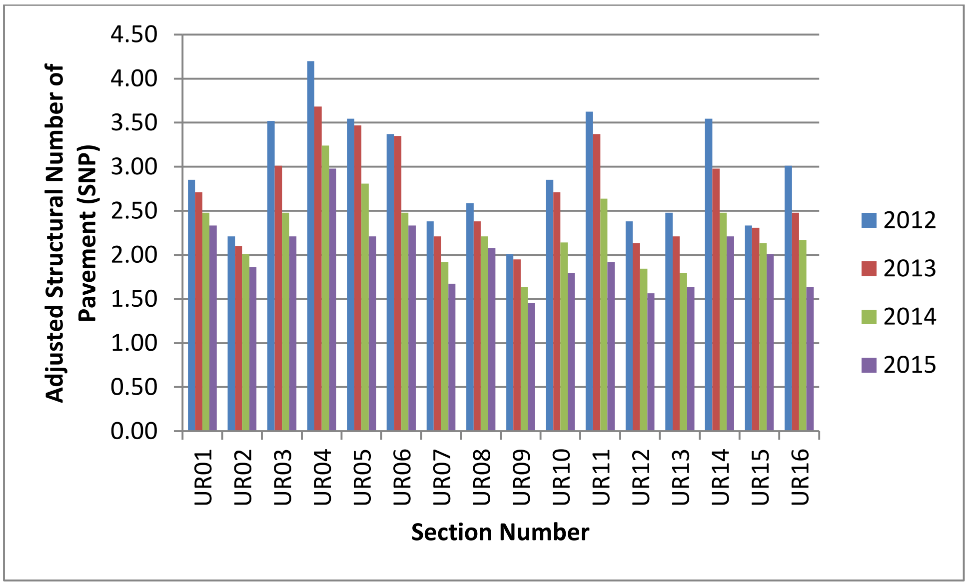


Fig. 3.13: Progressive variation of SNP for Road Sections UR01 to UR016

3.4.6.1 Cracking Measurement

Each section of 100 m representative length has been selected for cracking measurements for all the road sections from UR01 to UR016. Crack distress is measured by calculating the cracked area of pavement in terms of the total carriageway area in percentage. The area covered under the alligator cracking distress has been marked in the form of rectangular boxes on ground and each rectangular area is measured to calculate the percentage area cracked of a particular road section. In case of longitudinal and transverse cracks, minimum width of crack is considered to be 50 cm and length of distress has been measured by using tape. Figs. 3.14 - 3.17 show the cracks present on road section and measurement of cracks (Jyoti Mandhani & Tanuj Chopra, 2016). Fig. 3.18 shows progressive variation of cracking area for road sections UR01 to UR016.

Fig. 3.14: Transverse Cracking on Road Section

3.4.6.2 **Ravelling and Pothole Measurement**

Ravelling occurs when the laid bituminous mix lose the binding characteristics and loose aggregates appeared on the carriageway surface. It is measured in terms of ravelled area in percentage of total paved area. Fig. 3.19 shows the progressive variation of ravelling for road sections UR01 to UR016. Ravelling of a surface leads to another distress in terms of potholes which are visually measured for all road sections from UR01 to UR016. One standard pothole equals to 0.1 m^2 with minimum diameter of 150 mm and minimum depth of 25 mm. Fig. 3.17 & Fig. 3.20 shows the ravelling & potholes on section UR04 (Mohit Mantrao & Tanuj Chopra, 2013). Fig. 3.21 shows the progressive variations of potholes for road sections UR01 to UR016.The pothole measurements are finally expressed as number of pothole units per km length of the pavement section, as per HDM-4 data requirements.

Fig. 3.15: Cracked Surface

Fig. 3.16: Cracks on Section UR04

Fig. 3.17: Ravelled Surfaces

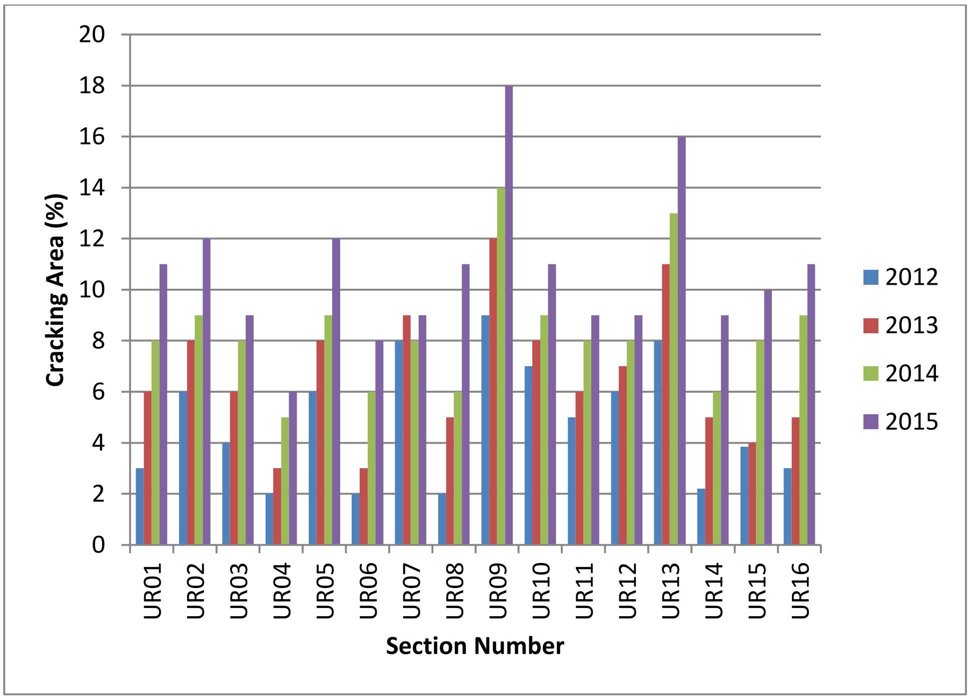


Fig. 3.18: Progressive variation of Cracking Area for Road Sections UR01 to UR016

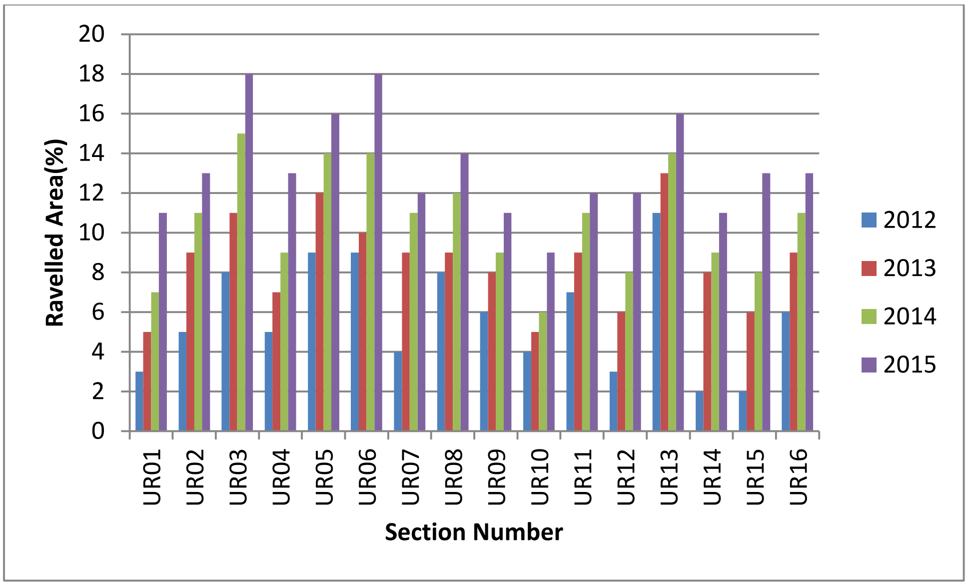


Fig. 3.19: Progressive variation of Ravelling Area for Road Sections UR01 to UR016

Fig. 3.20: Pothole on Section UR04

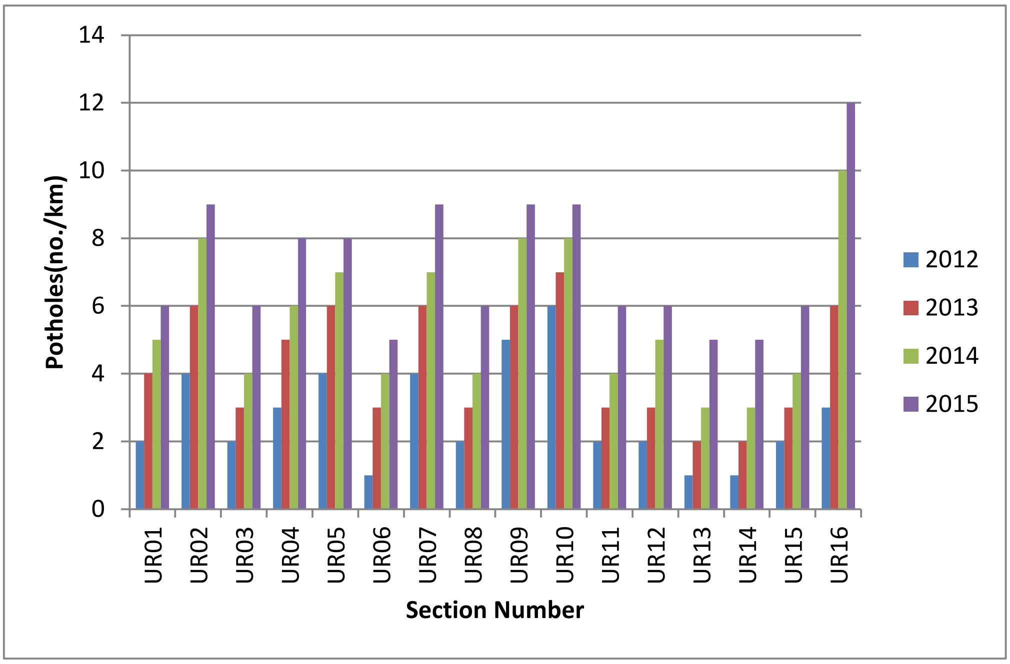


Fig. 3.21: Progressive variation of Potholes for Road Sections UR01 to UR016

3.4.6.3 Rutting Measurement

Rutting occurs because of the vertical compressive strain at the top of the subgrade and can also be because of the deformations with in the bituminous mixes. Rutting is known as a permanent deformation on pavement surface in the wheel path. The rut depth has been measured with 2 m straight scale placed in transverse direction of the carriageway. 12 times on each road section, rutting has been measured using straight edge particularly under the prominent wheel path. The average of the rut depths has been taken to get the mean rut depth of the road section. Figs. 3.22-3.24 show the rut depth measurement on different road sections (Mantrao 2013, Mandhani 2016). Fig. 3.25 shows the progressive variation of rut depth for various road sections from UR01to UR016.

Fig. 3.22: Rut Depth Measurement

Fig. 3.23: Rut Depth Measurement on Section

Fig. 3.24: Rut Depth Measurement on SectionUR03

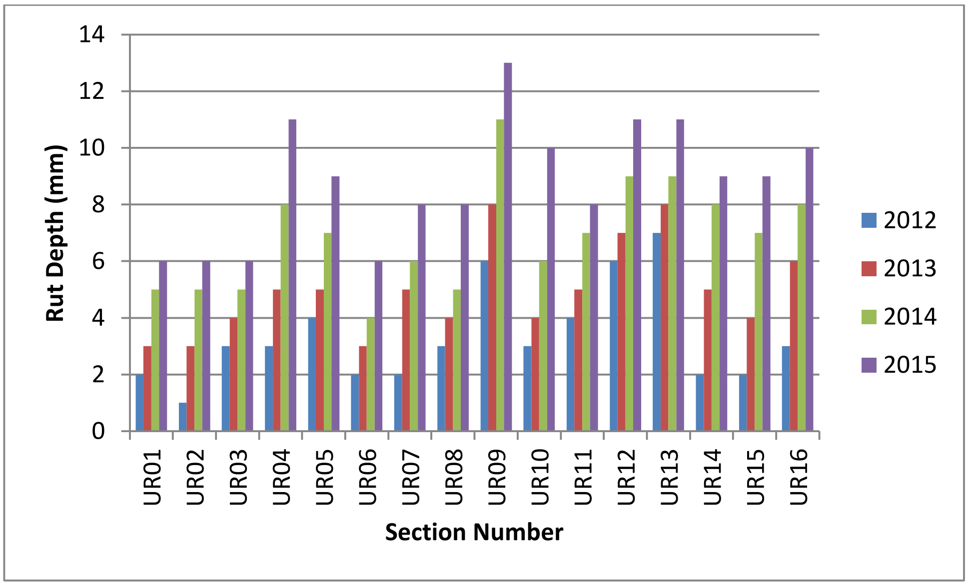


Fig. 3.25: Progressive variation of Rut Depth for Road Sections UR01 to UR016

3.4.6.4 Roughness Measurement

Roughness in terms of International Roughness Index (IRI) is used to define as the measurement of surface irregularities in the longitudinal profile of the road surface using Fifth Wheel Bump Integrator or Roughometer. In HDM-4, roughness values are entered as meters per kilometer (m/km). Roughness is an important pavement evaluation parameter because it affects not only ride quality but also vehicle operating costs, fuel consumption and maintenance costs. The standard codal specifications has been followed for conducting unevenness test with operational speed of the vehicle as 32 ± ½ km.p.h with standard tyre pressure. The equipment is towed by Pick-up and operated with speed of 32 km.p.h. The equipment towed by Pick-up has been made to run over wheel path (0.9 m distance from lane edge for two-lane and 1.5 m distance from lane edge for four-lane). Fig. 3.26– 3.29 shows the photos of Bump Integrator test performed on various road sections (Jyoti Mandhani & Tanuj Chopra, 2016). Accumulated Bumps (in cm) are noted down corresponding to length travelled (in km) for each road section from display panel board connected with equipment. Unevenness Index (in cm/km) has been calculated for each section by following equation.

Unevenness Index (UI) = Bumps in cm/ Length travelled in km **(3.3)**

To input the roughness values in to HDM-4 for all the 16 urban road sections, the obtained Unevenness Index (UI) value has been converted into International Roughness Index (IRI in m/km) by using the relationship given by Odoki and Kerali, 2000.

$$IRI = \left(\frac{1}{630} \times UI\right)^{1/1.12} \quad \textbf{(3.4)}$$

Where, UI is Unevenness Index in mm/km. IRI is International Roughness Index in m/km unit. Fig. 3.30 shows progressive variations of IRI for road sections UR01 to UR016.

Fig. 3.26: Bump Integrator (Roughometer) Towed with Pick-up

Fig. 3.27: Bump Integrator Test (Roughness Test) in Progress on Section UR03 (Chopra, T, Parida, M, Kwatra, N, Mandhani, J. (2017))

Fig. 3.28: Bump Integrator Test in Progress on Section UR03

Fig. 3.29: Bump Integrator Test in Progress on Section UR04

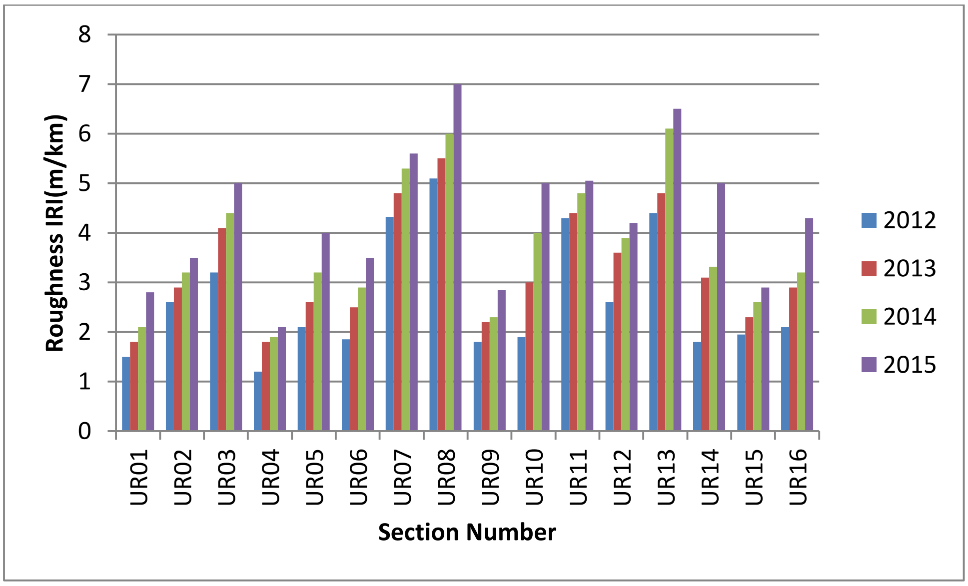


Fig.3.30: Progressive variation of IRI for Road Sections UR01 to UR016

3.5VEHICLE FLEET DATA

3.5.1 General

Both the motorized and non-motorized traffic has been considered for the analysis using HDM-4. A typical vehicle fleet in India may be considered to be comprised of the following vehicles for the purpose of economic analysis to be conducted in PMMS (Aggarwal 2004). The same vehicle set has also been entered in to HDM-4 as a representative vehicle fleet for Indian conditions, in the Updated Road User Cost Study (MORT&H 2001b). These vehicles are:

Motorized (MT) Vehicles

- Two Wheeler
- Car/Jeep/Van
- Bus(Medium)
- Mini Truck
- Mini Bus
- Truck
- Auto Rickshaw
- Tractor/Trolley

Non-Motorized Vehicles

- Cycle
- Man Driven Rickshaw
- Cart

3.5.2 Vehicle Fleet Database

The basic vehicle fleet data items (Archondo et al., 2003), which are required to be specified in HDM-4 has been given in Table 3.4 and Table 3.5 (Jyoti Mandhani & Tanuj Chopra, 2016) with reference to MORTH 2001 study. Complete vehicle data base information has been named as 'Patiala City Vehicle Fleet' and has been incorporated in to the vehicle fleet database of HDM-4 for running all the future modules of HDM-4.

Equivalent Single Axle Load Factor (ESALF) has been considered while calibrating the HDM 4 models and for generation of GP models by calculating the equivalent standard axle repetitions using the vehicle damage factor as per IRC guidelines.

Table 3.4: Basic Data of Motorized (MT) Vehicles included in Patiala City Vehicle Fleet

Vehicle Characteristics	Two - whe	Truks (Medium)	Mini Truck	Bus (Medium)	Mini Bus	Car/ Jeep/ Van	Tractor /Trolley
PCSE	0.5	1.4	1.3	1.5	1.2	1	1.3
Number of Wheels	2	6	4	6	4	4	4
Number of Axles	2	2	2	2	2	2	2

Annual no. of km driven	6000	85000	60000	10000	60000	30000	60000
Annual no. of Work hrs	150	2300	2000	2250	2000	1200	2000
Vehicle Service Life	7	9	9	8	9	10	9
No. of Passengers	1	0	0	40	20	4	0
Operating Weight	0.25	16.2	7.75	13.5	7.75	1.20	7.75
ESALF	0	6.44	0.34	0.55	0.02	0.0	3.6

Table 3.5: Basic Data of Non-Motorized (NMT) Vehicles in Patiala City Vehicle Fleet

Vehicle Characteristics	Cycle	Man-Driven Rickshaw	Cart
PCSE	-	-	-
Number of Wheels	2	3	2
Number of Axles	2	2	1
Annual no. of kilometers Driven	2500	7200	7200
Annual no. of Working Hours	150	500	500
Vehicle Service Life (Years)	10	6	6
No. of Passengers	0	2	2
Operating Weight (Tonnes)	0.1	.30	0.4
ESALF	0	0	0

3.6MAINTENANCE AND REHABILITATION WORKS

3.6.1 Serviceability Levels for Maintenance

To keep the road network to a certain level of serviceability, a suitable regular maintenance activities needs to be assigned by selecting a proper intervention level as per the IRC codal provisions. The maintenance serviceability levels for urban roads as per "Guidelines for Maintenance of Primary, Secondary and Urban Roads" (MORT&H, 2004) are given in Table 3.6.In the present study, all the sixteen road sections belong to Sub-Arterial and collector road category, so Serviceability Level as required according to type of roads has been adopted.

Table 3.6: Maintenance Serviceability Levels for Urban Roads

S.No.	Serviceability Indicator	Serviceability Levels		
		Arterial Roads	Sub-Arterials	Other
1.	Roughness by Bump Integrator (max. permissible)	2.8 m/km	4.0 m/km	5.2 m/km
2.	Potholes per km (max. number)	Nil	2-3	4-8

3.	Cracking and patching area (max. permissible)	5 percent	10 percent	10-15 percent
4.	Rutting – 20 mm (maximum permissible)	5mm	5-10 mm	10-20 mm
5.	Skid number (minimum desirable)	50 SN	40 SN	35 SN

*As per Odoki and Kerali (2000)

3.6.2 Maintenance & Rehabilitation (M&R) Treatments and Strategies

The function of maintenance is to preserve the pavement in a traffic worthy condition and to allow the movement of traffic at a requisite speed and safety. The maintenance strategies are based on assessment of needs with regard to the structural strength, condition and unevenness of surface and drainage. The main objective of maintenance management system is to provide an appropriate and economically viable maintenance strategies. Maintenance activities have been categorized as Ordinary Repairs (Routine Maintenance) and Periodic Renewals (Periodic Maintenance) as per the 'Guidelines for maintenance management of primary, secondary and urban roads.' (MORT&H 2004 &MORT&H 2001).

3.6.2.1 Routine Maintenance

Two major scheduled routine maintenance activities of crack sealing and Patch work has been entered in to HDM-4 of developing the maintenance management systems of Patiala urban road network.

- ***Crack Sealing***
  Crack sealing has several effects on future deterioration modeling (Aggarwal (2003)). The treatment comprises application of a slurry seal consisting of a mixture of emulsified bitumen and well-graded fine aggregates followed by rolling (MORT&H 2001)
- ***Patching***
  This is also a scheduled type, which is used to repair the surface distresses of potholing, structural cracking, and ravelling.

3.6.2.2 Periodic Maintenance

As per IRC 82 guidelines, early detection and repair of noticeable defects can prevent a major break-down of the surface. Periodic maintenance on the bituminous pavements consist of various treatments such as Preventive maintenance, Resealing, Resurfacing, Overlay, Milling and Reconstruction.

- ***Preventive Treatment***

  The preventive treatment is applied to the road surfaces so as to delay the distress initiation or progression of distresses. Preventive treatment of rejuvenation and fog seal is generally applied in terms of thin surface layer such as micro surface sealing so as to improve the quality of the pavement surface. This type of treatments are applied at very small amount of distresses or in the initial years of the life of bituminous pavements. Once the cracking or ravelling distresses exceeds the value of 5% & 10% respectively, other type of treatments are recommended as per MORTH guidelines. Liquid seal consists of an application of liquid bitumen (penetration grade, cut-back or an emulsion) and covering the same with aggregates and Fog seal is a light application of emulsified bitumen, usually without a cover aggregate. It is used to increase the binder content of bituminous surfaces, rejuvenate oxidised and old surfaces, fill in cracks and prevent ravelling as per IRC 82 guidelines.

- ***Resealing***

  Resealing can be used to improve the quality of bituminous surface by resetting the small range distress parameters such as cracking, ravelling and roughness. Resealing in form of thin surfacing such as 20 to 30 mm Single Coat Bituminous Surface Dressing (SBSD) has been used commonly on the urban road sections of India as per IRC 17 guidelines which consists of a single application of bituminous binder, followed by laying of aggregate layer and compaction by suitable rollers as per IRC guidelines. In case of the Double Bituminous Surface Dressing (DBSD), all the above procedure has to be completed for two course layers. Effect of such maintenance activities reset the value of roughness of 2m/km (Morosiuk et al., 2001).

- ***Overlay***

  Overlay for the flexible pavements is generally provided in terms of Semi Dense Bituminous Concrete layer (SDBC) and Bituminous Concrete (BC) layer to strengthen the existing pavements. The thickness required for the overlay has been calculated as per the IRC 81 guidelines based upon the traffic repetition and characteristic deflection of the pavement surface.

  The mix characteristic & construction specifications of both BC & SDBC layers should be as per the IRC codal specifications with SDBC having lesser binder content as compared to BC layer. For low traffic volumes, the overlay can also be provided in terms of open graded premix carpet as per the MORTH guidelines generally in thickness of 20mm or 40 mm.

After the applications of these overlays, the rut depth value resets to 15 percent of the before treatment value and roughness values gets resets to 2.0m/km (Morosiuk et al., 2001).

- ***Mill and Replace***

  In the milling operation, part of the existing bituminous surfacing is milled and is replaced with a new bituminous surfacing. Value of surface distresses and rut depth value get reset to zero after the application of mill and replace maintenance work.

  The maintenance work effects of bituminous concrete overlays resets the value of roughness to 2.0 m/km as default value after BC overlay works (Morosiuk et al., 2001)

- ***Reconstruction***

  Pavement reconstruction means to reconstruct all the different layers of pavement crust starting from subgrade reconstruction as per the revised axle load repetitions and traffic volume. Crust thickness and material specifications are to be provided as per the detailed design of the pavement section. IRC guidelines are to be used for designing the new pavement sections for a particular design life based upon cumulative standard axle load repetitions.

  After reconstruction, all the surface distresses values gets reset to zero value and value of roughness gets resets to 2.0 m/km which are similar to mill and replace treatment (Morosiuk et al., 2001) but the rate of progression of surface distresses like cracking, potholes, ravelling, edge break and roughness will be on slower pace after reconstruction treatment as compared to milling and replace treatment works.

The present cost of various M&R works is as given in Table 3.7 calculated as per the Government of India, CPWD-DSR-2016.

Table 3.7: Cost Data of M&R Works

S. No.	Type of M&R Work	Cost per sq. m of Surface Area (in Rupees)
Routine Maintenance		
1.	Crack Sealing (All Cracks)	66.4
2.	Pothole Patching	84.7
3.	Rutting and Undulation Repair	117.7
4.	Tack Coat	13.5
5.	Liquid Seal Coat	68.8
Periodic Maintenance		
1.	Single Bituminous Surface Dressing (SBSD)	178.5
2.	Double Bituminous Surface Dressing (DBSD)	248.7
3.	Premix Carpet (20mm PC)	180.2
4.	Mix Seal Surfacing (20 mm MSS)	200.6
5.	Semi Dense Bituminous Concrete (25mm SDBC)	260.1
6.	Bituminous Concrete (25mm BC)	295.6
7.	Bituminous Concrete (40mm BC)	369.0
8.	Bituminous Macadam (50mm BM)	370.5
9.	Dense Bituminous Macadam (75mm DBM)	514.5
10.	Mill 90mm and Replace with (BM 50mm + BC 40mm)	639.4
11.	200 mm Wet Mix Macadam + 75 mm Dense Bituminous Macadam + 40mm Bituminous Concrete	1429.8

(Source: Chopra, T, Parida, M, Kwatra, N, Mandhani, J. (2017))

3.7 CALIBRATION OF HDM-4 PAVEMENT DETERIORATION MODELS

The calibration factors of inbuilt HDM-4 road deterioration models have been calculated for different pavement compositions by using standard equations of HDM-4 and the equations used for calculation of Calibration factors are presented in Table 3.8.

Table 3.8: HDM-4 Pavement Deterioration Models of Cracking Progression, Ravelling Progression, Pothole Progression and Roughness Progression

Model	Equation
Cracking Progression	$dACA = K_{cpa}\left(\frac{CRP}{CDS}\right)[\left(1.07 \times 0.28 \times \delta tA + SCA^{0.28}\right)^{\frac{1}{0.28}} - SCA$
Ravelling Progression	$dARV = [\frac{K_{vp}}{RRF}][\frac{1}{CDS^2}][(0.6 + 3.0 * YAX) * 0.352 * \delta tv + SRV^{0.35})^{\frac{1}{0.35}} - SRV]$
Potholing Progression	$dNPTi = Kpp^* ADIS_i(TLF)[\frac{(1\ 1*CDB)(1\ 10*YAX)(1\ 0.005*MMP)}{(1\ 0.08*HS)}]$
Rut depth Progression	$\Delta RDM = K_{rst\ [0.0000248} \times SNP^{-0.84} \times YE4^{0.14} \times MMP^{1.07} \times ACX_a^{1.11}$
Roughness Progression **(For AC surfacing)**	$\Delta IRI = K_{gp}[134 \times exp\left(m\, K_{gm}\, AGE3 \times (1 + SNPK_b)^{-5}\, YE4\right] + [0.0066 \times \Delta ACRA] + [0.088 \times \Delta RDS] + [0.00019(2 - FM)\{((NPT_a \times TLF) + \left(\Delta NPT \times \frac{TLF}{2}\right))^{1.5} - (NPT_a)^{1.5}\}] + [mK_{gm}RI_a]$

Where,

- CDS = Construction defects indicator for bituminous surfacing (0.5 = brittle, 1.0 = optimum, 1.5 = soft)
- SNP = Average annual adjusted structural number of pavement
- YE4 = Annual number of equivalent standard axles, in millions/lane
- CRT = Crack retardation time due to maintenance, in years (default value = 1.5)
- dACA = Incremental change in area of all cracking during year, in percent of total carriageway area.
- CRP = Retardation of cracking progression due to preventative treatment, given by [CRP = 1-0.12CRT]
- SCA = Min.{ACAa, (100-ACAa)}
- δtA = Fraction of analysis year in which all cracking progression applies
- ACAa = Area of all cracking of the start of the analysis year, in percent
- IRV = Time to ravellng initiation, in years
- YAX = Annual number of axles of all vehicle classes in the analysis year, in millions/lane
- RRF = Ravelling retardation factor due to maintenance (default value = 1.0)
- dARV = Change in area of ravelling during analysis year, in per cent of total carriageway area
- SRV = Min. {ARVa, (100 – ARVa)}
- δtv = Fraction of analysis year in which ravelling progression applies
- ARVa = Area of ravelling at the start of the analysis year, in per cent
- HS = Total thickness of bituminous surfacing
- CDB = Construction defects indicator for the base (0 = no defects, 1 = some defects, 1.5 = several defects)

- MMP = Mean monthly precipitation, in mm/month (average value = 80 mm)
- dNPTi = Additional number of potholes per kilometer derived from distress type i
- TLF = Time lapse factor depending upon the frequency of pothole patching (default value = 1.0)
- ADISi = Percent area of wide cracking at start of the analysis year, or percent area of ravelling at the start of analysis year, or number of existing potholes per km at start of the analysis year
- m = Environmental co-efficient (default value = 0.025)
- AGE3 = Age since last overlay or reconstruction, in years
- SNPKb = Adjusted structural number due to cracking at end of analysis year
- ΔACRA = Incremental change in area of total cracking during analysis year, in percent
- ΔRDS = Incremental change in standard deviation of rut depth during analysis year, in mm
- FM = Freedom to maneuver index based on carriageway width in m and AADT
- AADT = Two-way traffic flow, in vehicle/day
- ΔNPT = Incremental change in number of potholes per km. during analysis year
- NPTa = Number of potholes per km at start of the analysis year
- ΔRI = Total incremental change in roughness during analysis year, in m/km IRI
- RIa = Roughness at the start of the analysis, in m/km IRI
- K_{gm} = Calibration factor for the environmental component of roughness (default value = 1.0)
- M= environmental coefficient
- t= time since latest overlay or construction
- SNCK= modified structural number for the pavement, reduced for the effect of cracking
- ΔCRX=annual incremental change in the year of indexed cracking in percent
- ΔPOT = annual incremental change in the year of potholing in percent
- K_{gp}= calibration factor for roughness progression
- ΔRDM = change in total mean rut-depth in both wheel paths in the analysis year in mm
- K_{rst} = Calibration factor for structural component of rutting (default value = 1.0)

For known set of readings of dACA, dARV, $dNPT_i$ and ΔIRI for year 2012, 2013, 2014, 2015 K_{cpa}, K_{vp}, K_{pp}, K_{gp} are calculated and are used for the design of PMMS for the Urban Roads of Patiala.

3.7.1 Calculation of Calibration factor

For determining the calibration factors for Cracking (K_{cpa}), Ravelling (K_{vp}), Potholling (K_{pp}), Rutting (K_{rst}) and Roughness (K_{gp}), data of 16 road sections of Patiala city has been considered (Table 3.1) and their distresses values are taken from the experimental values. HDM-4 has been run for representative sections with road network and vehicle fleet input data. The range of calibration factors as suggested by HDM-4 varies from 0 to 20 with default value of 1. As reviewed from past studies the calibration factors for urban roads varied from zero to two for Indian conditions. Hence, in the first stage of calibration HDM-4 has been run for factors varying from 0 to 5 with an increment of 0.20. Calibration factors have been then determined from the results of first run corresponding to minimum Root Mean Square Error (RMSE) and maximum Coefficient of Determination (R^2) as shown in Table 3.11.After getting the calibration factors from first run, the HDM-4 has been run for the second stage by taking the calibration factors within the closer range of factors with an increment of 0.01. An analysis of verification of prediction quality of model has been performed by comparing observed values versus predicted distresses for each of the models. The comparisons have been made with the generalized average factors for the study area. Generalized Calibration progression factor(GCF) as average of 4 different sets based upon road traffic and age as given in Table 3.9) as K_{cpa} as 0.44, K_{pp} as 1.18, K_{vp} as 0.13, K_{rst} as 2.71 and K_{gp} as 2.45 has been calculated for cracking, potholing, raveling, rutting & roughness for the Patiala city as shown in Table 3.10.The calculated calibration factorshave been used when no maintenance is applied and the results obtained have been compared with the actual value of distress for the nextyears.

Table 3.9: Details of Groups defined for the Study Area

Group 1	Group 2	Group 3	Group 4
Commercial traffic less than 7 percent		Commercial traffic more than 7 percent	
Age 0-6 years	Age 7 to 12 years	Age 0-6 years	Age 7 to 12 years
UR08, UR010, UR016	**UR02, UR04, UR06, UR012, UR014**	**UR01, UR03, UR05, UR011**	**UR07, UR09, UR013, UR015,**

Table 3.10: Suggested Calibration Factors for Patiala City

Group	K_{cpa}	K_{vp}	K_{pp}	K_{rst}	K_{gp}
1	0.50	0.09	1.36	2.64	2.63
2	0.40	0.14	1.26	2.64	2.75
3	0.46	0.13	1.21	2.74	2.42
4	0.40	0.16	0.92	2.83	2.01
GCF	**0.44**	**0.13**	**1.18**	**2.71**	**2.45**

Table 3.11: Statistical indicator for Calibration

Group	Cracking Progression		Raveling Progression		Pothole Progression		Rut depth progression		Roughness Progression	
	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2	RMSE	R^2
1	0.65	0.98	0.89	0.79	0.81	0.89	0.83	0.81	0.60	0.99
2	0.88	0.96	0.95	0.77	1.41	0.70	0.94	0.86	0.31	0.90
3	0.94	0.71	0.33	0.98	1.58	0.93	0.22	0.96	0.37	0.89
4	0.83	0.88	1.03	0.87	0.70	0.93	1.04	0.95	0.42	0.98

3.7.2 Validation of HDM-4 Road Deterioration Models

The calibrated HDM-4 pavement deterioration models need to be validated before using the calibration factors for developing the PMMS in the present study. For validation purpose the observed and HDM-4 model predicted values of distresses for the year 2014 have been compared for all the road sections of urban network. The linear regression relationship between the observed and predicted distresses has been developed by plotting the scatter plots as presented in Fig. 3.1 - 3.5. The coefficient of determination R^2 varies between 0.71- 0.92 and RMSE varies between 0.92 - 1.3 for all the validated models and the details are given in Table 3.17. This shows a good agreement between observed and predicted distresses and hence proves the adequacy of the calibrated HDM-4 deterioration models for the urban roads in the study area. The details of observed and HDM-4 predicted distresses and the percentage variability between them for validating the calibrated models for the selected urban roads are given in Table 3.12 - 3.16.The percentage variability obtained between the observed and predicted distresses such as for cracking area ranges between 2.16 to 21.66 percent, for ravelling ranges between 0.27 to 25.7 percent, for pothole ranges between 0.0 to 30.0 percent, for rut depth 3 to 32 percent and for roughness ranges between 0.34 to 27.82 percent, which is quite reasonable for urban road sections of different age and traffic loading conditions.Further to check the goodness-of-fit between the observed and predicted distresses a Chi-square test has been performed. The $\chi^2_{calculated}$ for various distress models for selected urban roads have been compared with $\chi^2_{critical}$ values for level of significance (α) of 5% and degree of freedom as (N-1), and the results of the same are given in Table 3.17. Since the calculated value of χ^2 for all the models is less than critical value of χ^2, H_o hypothesis is accepted and it has been concluded that there is significant relationship between the observed and HDM-4 predicted distresses *i.e,* they have no statistical difference.

Table 3.12: Details of Observed and Predicted Distresses and Percentage Variability of Cracking

Group	Section ID	Observed Cracking	Predicted Cracking	Variability (%)
1	**UR08**	6	5.87	2.16
	UR010	9	10.95	21.66
	UR016	8	7.17	10.375

2	**UR 02**	9	10.54	17.11
	UR04	5	5.54	10.80
	UR06	6	5.54	7.66
	UR012	8	9.22	15.25
3	**UR01**	8	8.2	2.5
	UR03	8	8.2	2.5
	UR05	9	10.6	17.77
	UR011	8	8.25	3.12
4	**UR07**	11	11.55	5
	UR09	14	15.48	10.57
	UR013	13	13.92	7.07
	UR015	7	5.5	21.42

Table 3.13: Details of Observed and Predicted Distresses and Percentage Variability of Ravelling

Group	Section	Observed	Predicted	Variability
1	**UR08**	12	11	8.33
	UR010	6	6.35	5.83
	UR016	11	10.97	0.27
2	**UR02**	11	12.15	10.45
	UR04	9	9.84	9.33
	UR06	14	13.43	4.07
	UR012	8	8.57	7.125
3	**UR01**	7	7.16	2.28
	UR03	15	14.27	4.86
	UR05	14	15.38	9.85
	UR011	11	11.93	8.45
4	**UR07**	11	12.63	14.81
	UR09	9	11.32	25.77
	UR013	14	17.38	24.14
	UR015	8	9.04	13

Table 3.14: Details of Observed and Predicted Distresses and Percentage Variability of Potholes

Group	Section	Observed	Predicted	Variability
1	**UR08**	4	4	0
	UR010	8	10	25
	UR016	8	7	12.5
2	**UR02**	7	8	14.28
	UR04	6	6	0

	UR06	4	4	0
	UR012	5	4	20
3	**UR01**	5	4	20
	UR03	5	4	20
	UR05	10	7	30
	UR011	5	4	20
4	**UR07**	7	7	0
	UR09	8	9	12.5
	UR013	3	3	0
	UR015	5	5	0

Table 3.15: Details of Observed and Predicted Distresses and Percentage Variability of Rut Depth

Group	Section	Observed	Predicted	Variability
1	**UR08**	5	5.23	4.60
	UR010	9	7.64	15.11
	UR016	10	6.96	30.40
2	**UR02**	5	4.11	17.8
	UR04	8	5.44	32
	UR06	4	4.12	3
	UR012	9	8.51	5.44
3	**UR01**	5	3.94	21.2
	UR03	5	4.6	8
	UR05	7	6.18	11.71
	UR011	7	6.11	12.71
4	**UR07**	6	6.24	4
	UR09	11	10.25	6.81
	UR013	9	9.84	9.33
	UR015	8	6.28	21.50

Table 3.16: Details of Observed and Predicted Distresses and Percentage Variability of Roughness

Group	Section	Observed	Predicted	Variability
1	**UR08**	6	6.67	4.6
	UR010	4	3.37	15.11
	UR016	3.2	3.2	30.4
2	**UR02**	3.2	3.61	12.81
	UR04	1.9	2	5.26

	UR06	2.9	2.91	0.34
	UR012	3.9	4.52	15.89
3	**UR01**	2.1	2.24	6.66
	UR03	4.4	4.33	1.59
	UR05	3.2	3	6.25
	UR011	4.8	4.74	1.25
4	**UR07**	5.3	5.26	0.75
	UR09	2.3	2.94	27.82
	UR013	6.1	5.45	10.65
	UR015	2.6	3.05	17.30

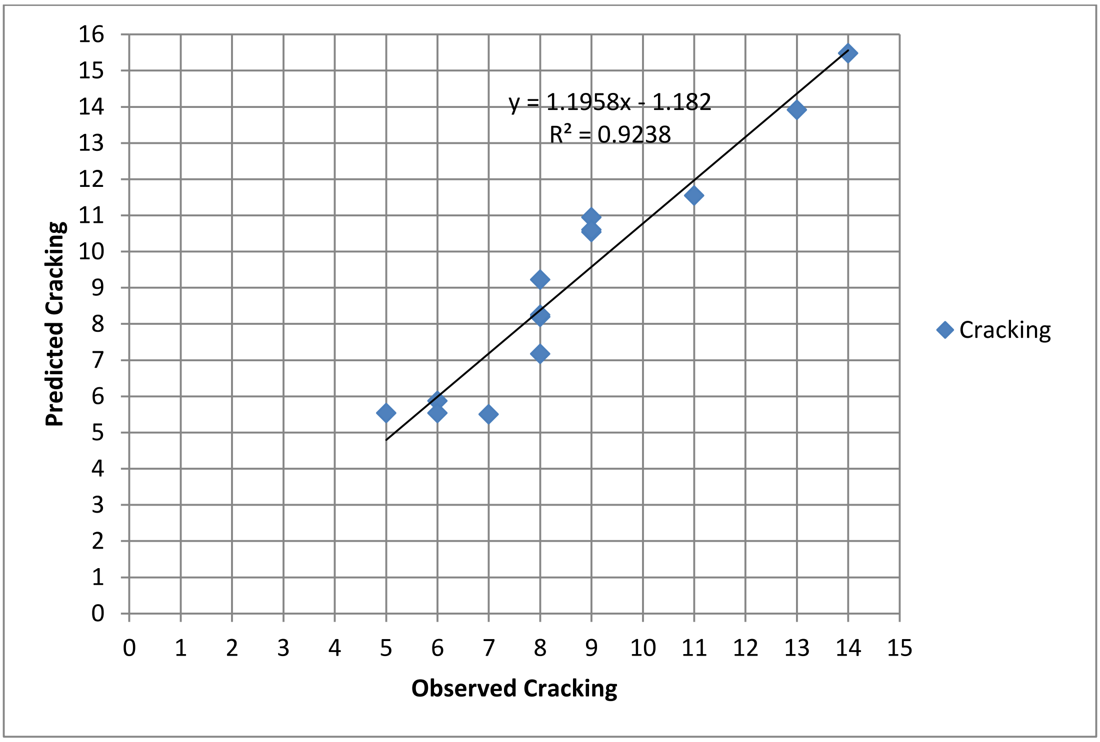


Fig. 3.31: Scatter Plot between Observed vs. Predicted Cracking for Validation

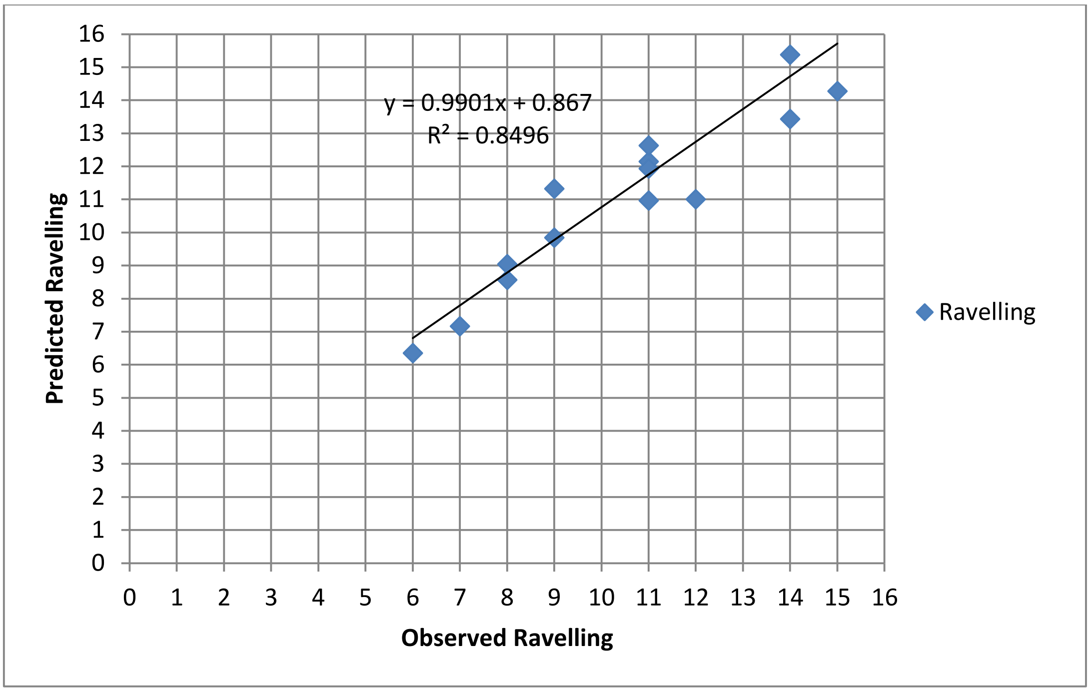


Fig. 3.32: Scatter Plot between Observed vs. Predicted Ravelling for Validation

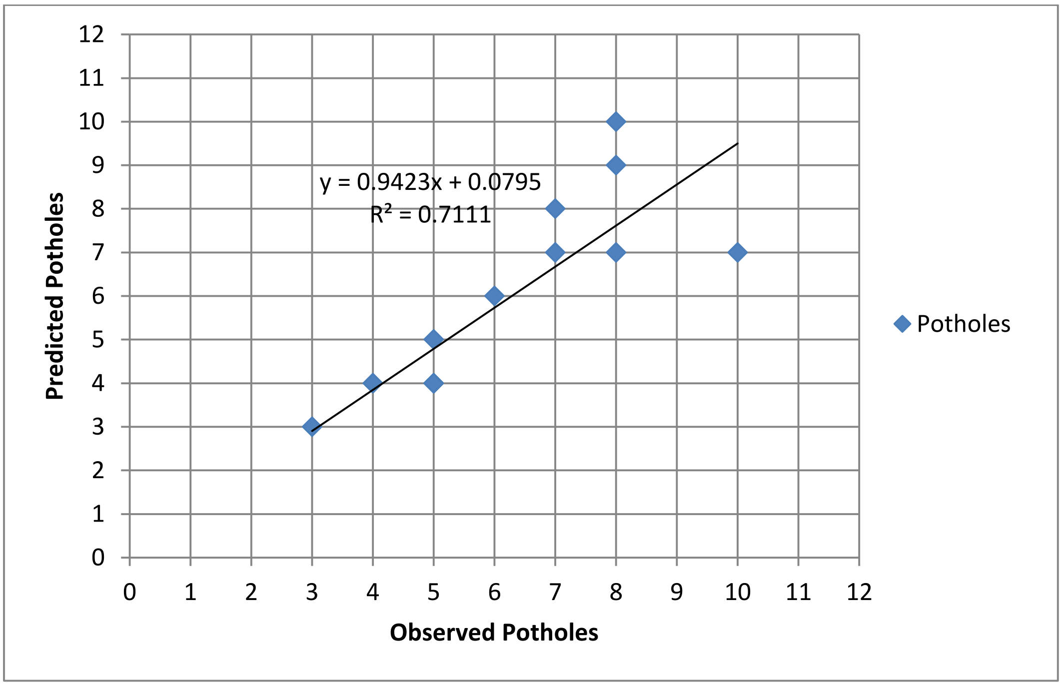


Fig. 3.33: Scatter Plot between Observed vs. Predicted Potholes for Validation

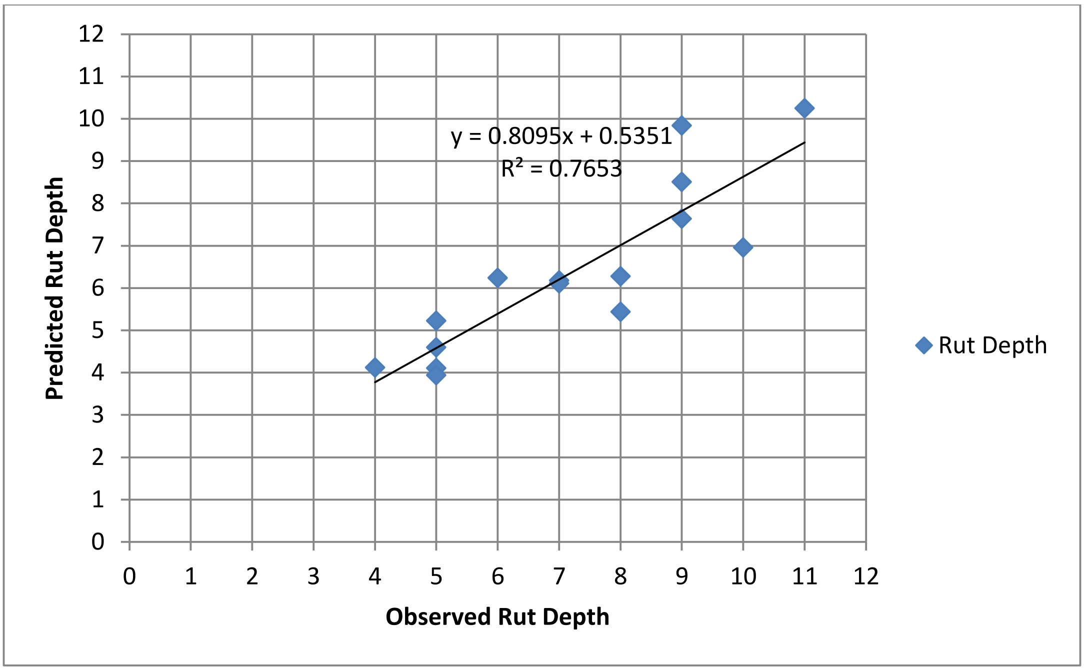


Fig. 3.34: Scatter Plot between Observed vs. Predicted Rut Depth for Validation

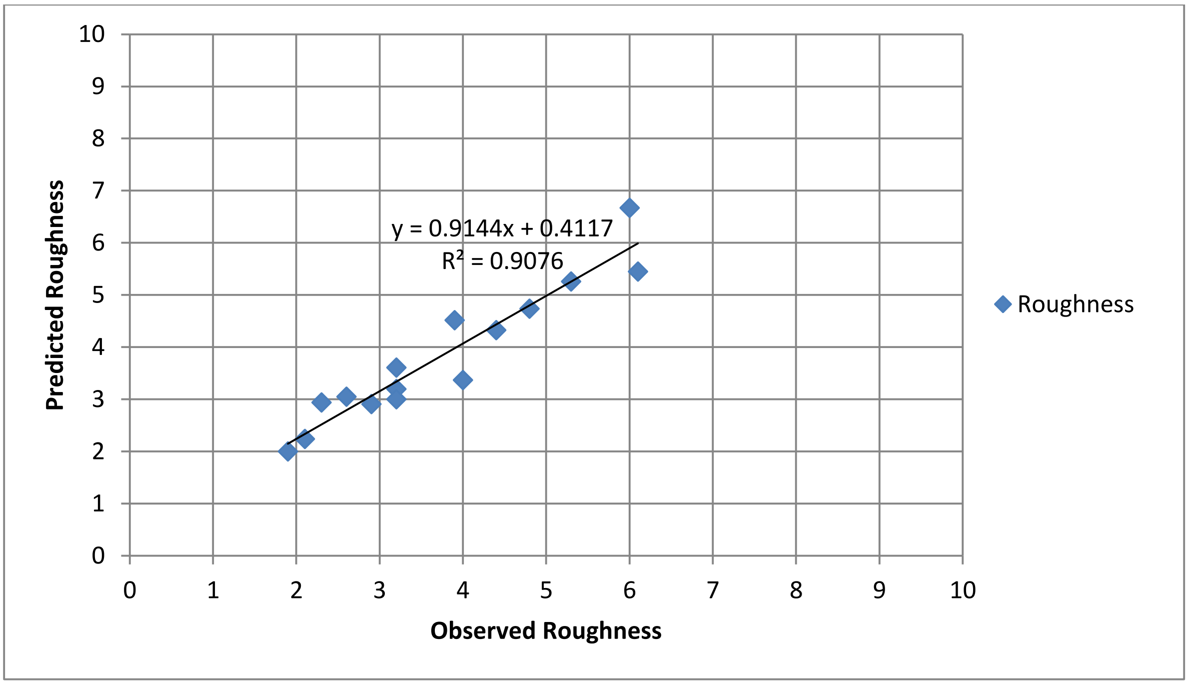


Fig. 3.35: Scatter Plot between Observed vs. Predicted Roughness for Validation

Table 3.17: Statistical Indicators for Validation of Calibrated Pavement Deterioration Models

S. No	HDM MODEL	LINEAR REGRESSION	χ^2 calculated	χ^2 critical	DOF	R^2	RMSE
1	Cracking Progression	y = 1.195x - 1.182	1.819	23.685	14	0.923	1.06
2	Ravelling progression	y = 0.990x + 0.867	2.053	23.685	14	0.849	1.35
3	Pothole Progression	y = 0.942x + 0.079	3.065	23.685	14	0.711	1.15
4	Rut Depth Progression	y = 0.809x + 0.535	4.174	23.685	14	0.765	1.31
5	Roughness Progression	y = 0.914x + 0.411	0.629	23.685	14	0.907	0.92

3.7.3 Results and Discussions of Calibration

On the basis of the above statistical results, the efficacy of the calibrated HDM-4 deterioration models for the urban road network has been established. The rate of progression of cracking and ravelling, are slower by 56% & 87% respectively than those predicted by default HDM-4 models. However, the rate of progression of potholing, rutting and roughness is faster by 18%, 171% and 145% than that predicted by default calibration factor of 1 by HDM-4.Therefore, it is concluded that the above deterioration models can be used for prediction of distresses and the development of maintenance management strategies for the selected road network. The statistical indicators likeR^2 and RMSE as given in Table 3.17 shows a good agreement between observed and predicted distresses from calibrated HDM-4 analysis. The R^2 values for all types of distress models varies between a range of 0.711 to 0.923 which are reasonably accepted for pavement network condition with varying age, traffic loading and other factors. Hence, the suggested calibration factors for HDM-4 pavement deterioration models holds good and shall be useful for developing the pavement maintenance management system for the urban road network.

CHAPTER 4

DEVELOPMENT OF PAVEMENT MANAGEMENT SYSTEM (PMMS) USING HDM-4

4.1 GENERAL

The methodology for developing Pavement Maintenance Management System (PMMS) of Patiala City road network using HDM-4 model has been discussed in the previous chapter. The pavement maintenance and management plays a very important role to keep the pavements within the serviceability levels both at the project level considering detailed maintenance management practices. PMMS at project level solve various maintenance management issues related to the selection of the optimal maintenance solutions and to determine the cost effectiveness of various maintenance alternatives. Application of HDM-4 software at project level for developing PMMS of Patiala road sections has been discussed in this chapter.

4.2 USE OF HDM-4 APPLICATION MODULES FOR PMMS

In this study, PMMS has been developed by analyzing the projects using 'Project Analysis' application module of HDM-4 and the total life cycle cost assessment for next 10 years has been carried out using Program Analysis application module of HDM-4. In the present study, the following types of objectives have been undertaken for the project level analysis of sixteen road sections of Patiala city road network.

- Determination of Remaining Service Life (RSL) of selected road sections of Patiala city road network.
- Determination of Optimum Maintenance and Rehabilitation (M&R) Strategy for all the selected road sections.
- Prioritization of the selected road sections for maintenance work based on optimum M&R strategy.
- Comparative Study of Scheduled type and Condition Responsive type M&R strategy for individual road section.
- Program Analysis to compare the life-cycle cost of the pavement network, including the road agency costs (RAC) and road user costs (RUC).

4.3 ROAD NETWORK AND VEHICLE FLEET DATA INPUT IN HDM-4

The basic data input in HDM-4 are Road Network and Vehicle Fleet Data. Road Network refers to the network having number of road sections with their characteristics. Vehicle Fleet Data refers to representation of vehicles and their characteristics.

4.3.1 Road Network

For the present study, Road Network named as ‘Patiala City Road Network’ has been created. 16 road sections with Section ID UR01-UR016 have been entered in HDM-4 as shown in Fig. 4.1. Each road section with its definition, geometry, pavement and condition data (mentioned in previous chapter) has been inputted. Prior to this, Traffic Flow patterns have been created in Configuration part. Climate Zone ‘North India Plain’ has been selected for the study. The traffic detail entry in HDM-4 has been shown with the help of Fig. 4.2. Figs. 4.3 present data entry of the road parameter, pavement and condition of road for UR01, respectively. The same procedure is followed to enter the data for the entire selected road network. This road network has been further used to determine the objectives.

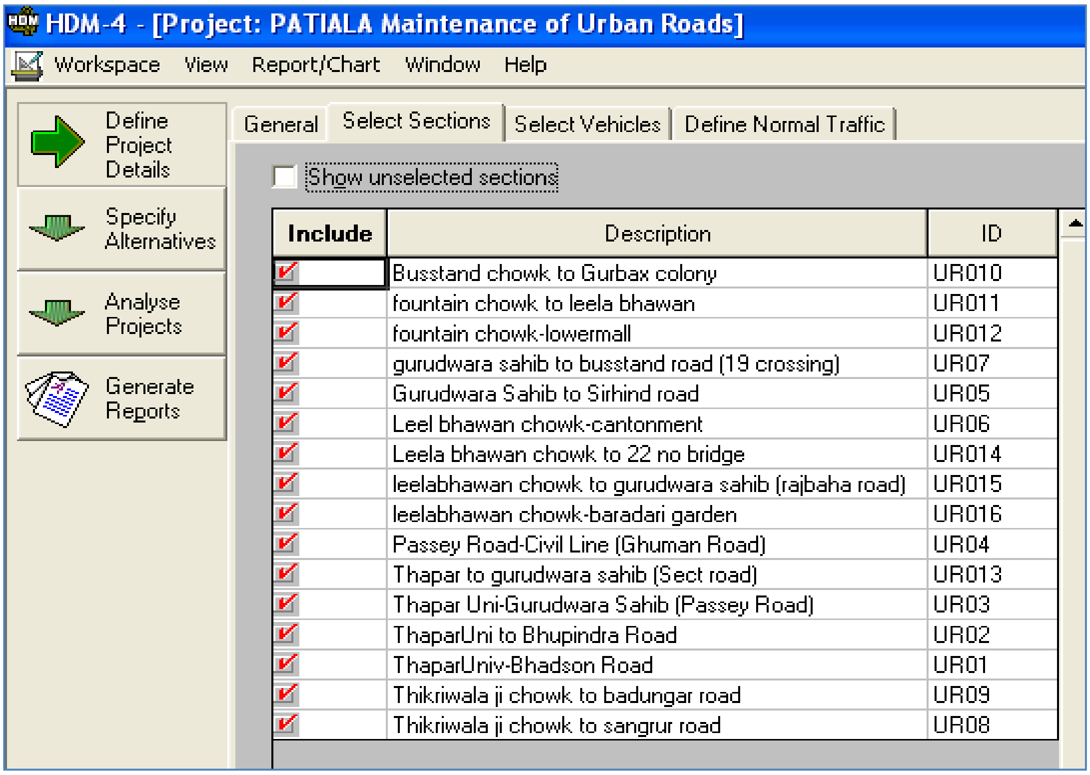


Fig. 4.1: Selected Road Network of Patiala City

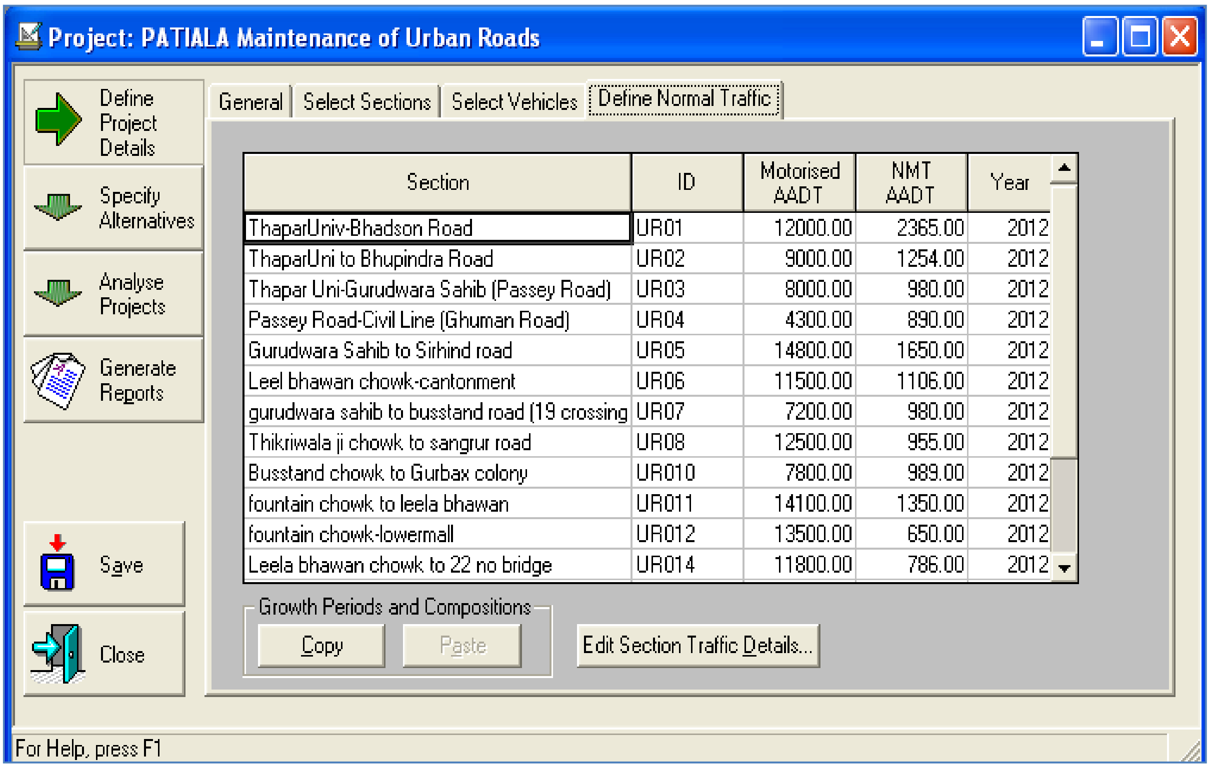


Fig. 4.2: Traffic Details for the Patiala City Road Network

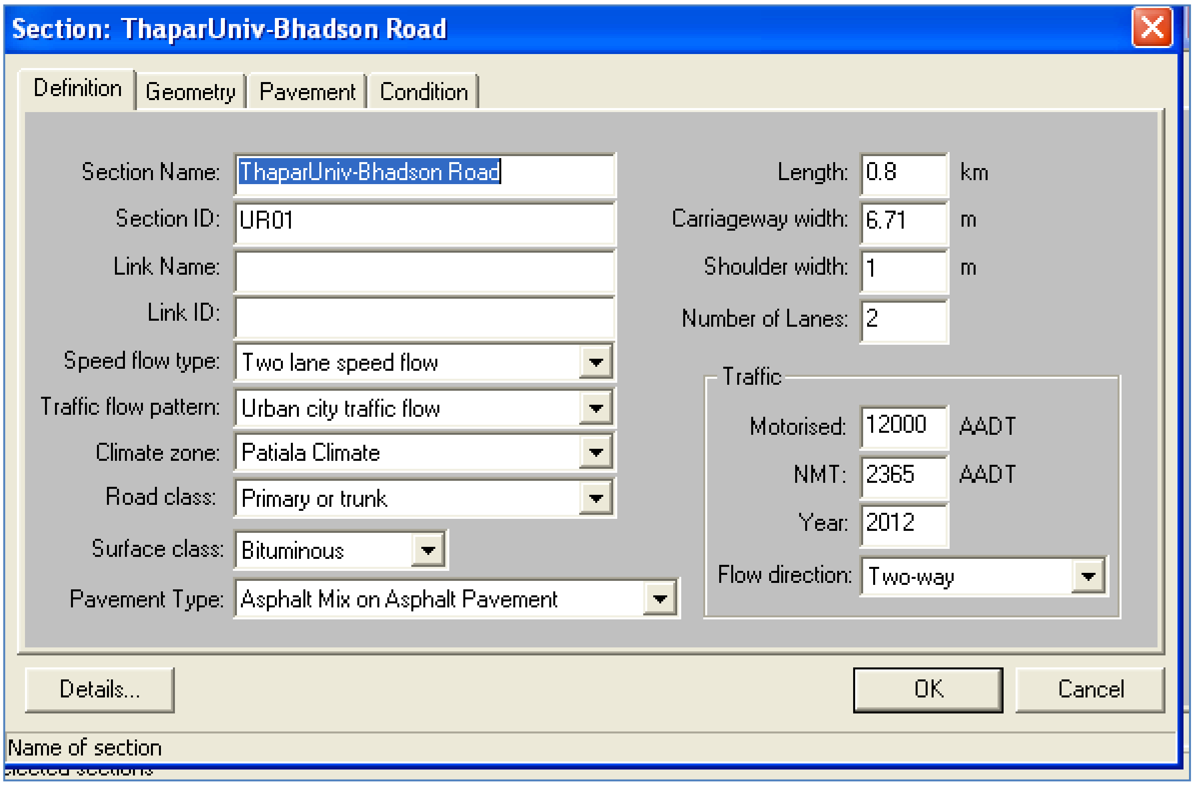


Fig. 4.3: Road Parameter Data Entry for UR01

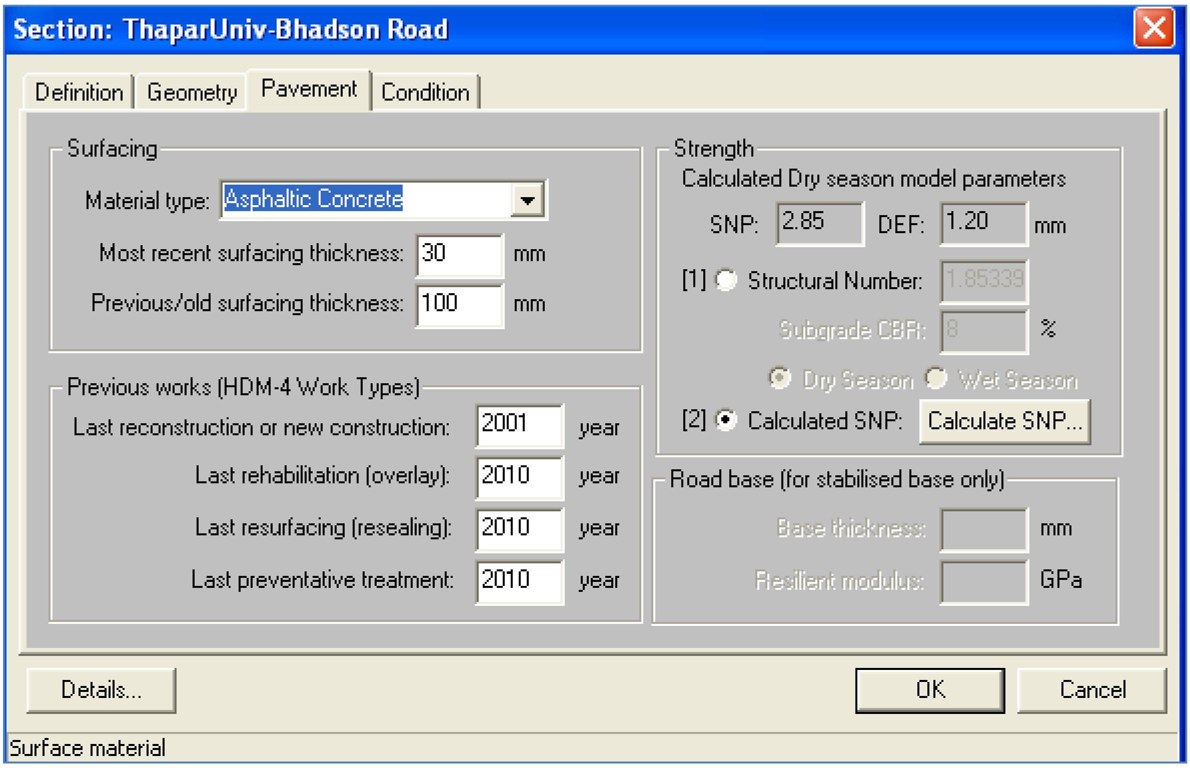


Fig. 4.4: Pavement Data Input Entry for UR01

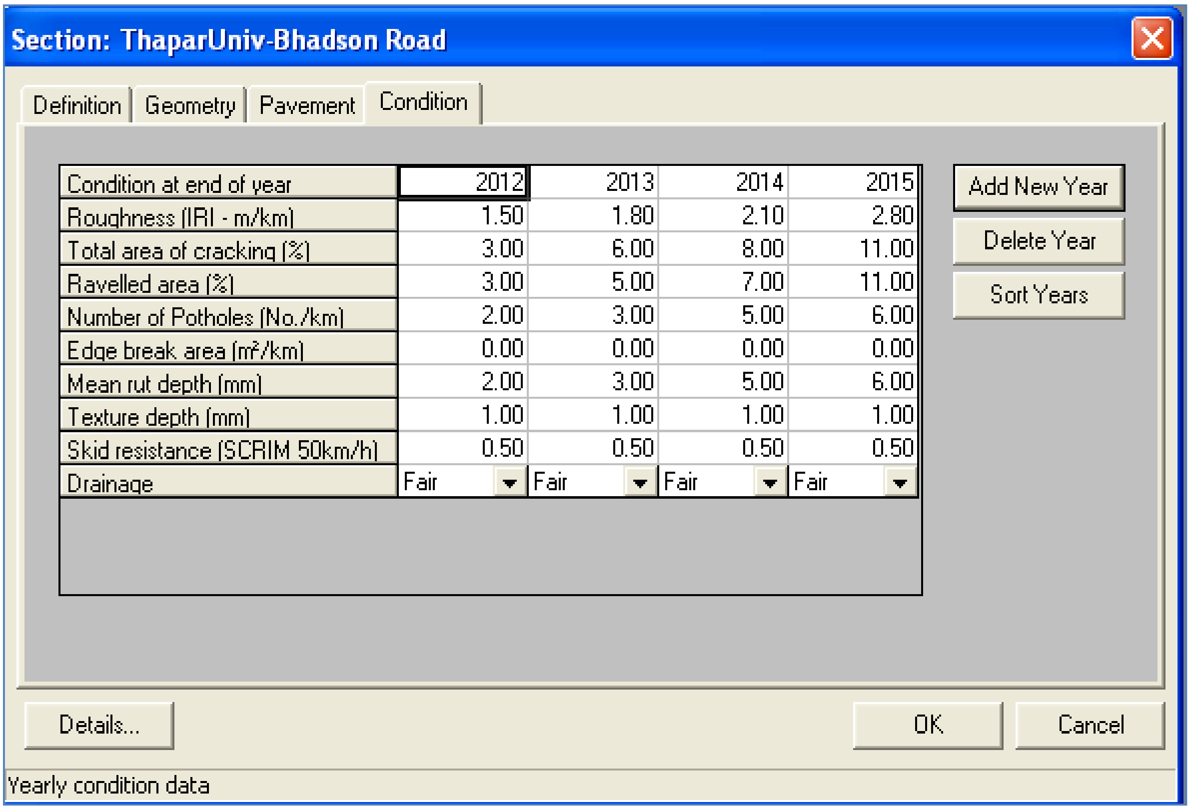


Fig. 4.5: Condition Data Input Entry for UR01

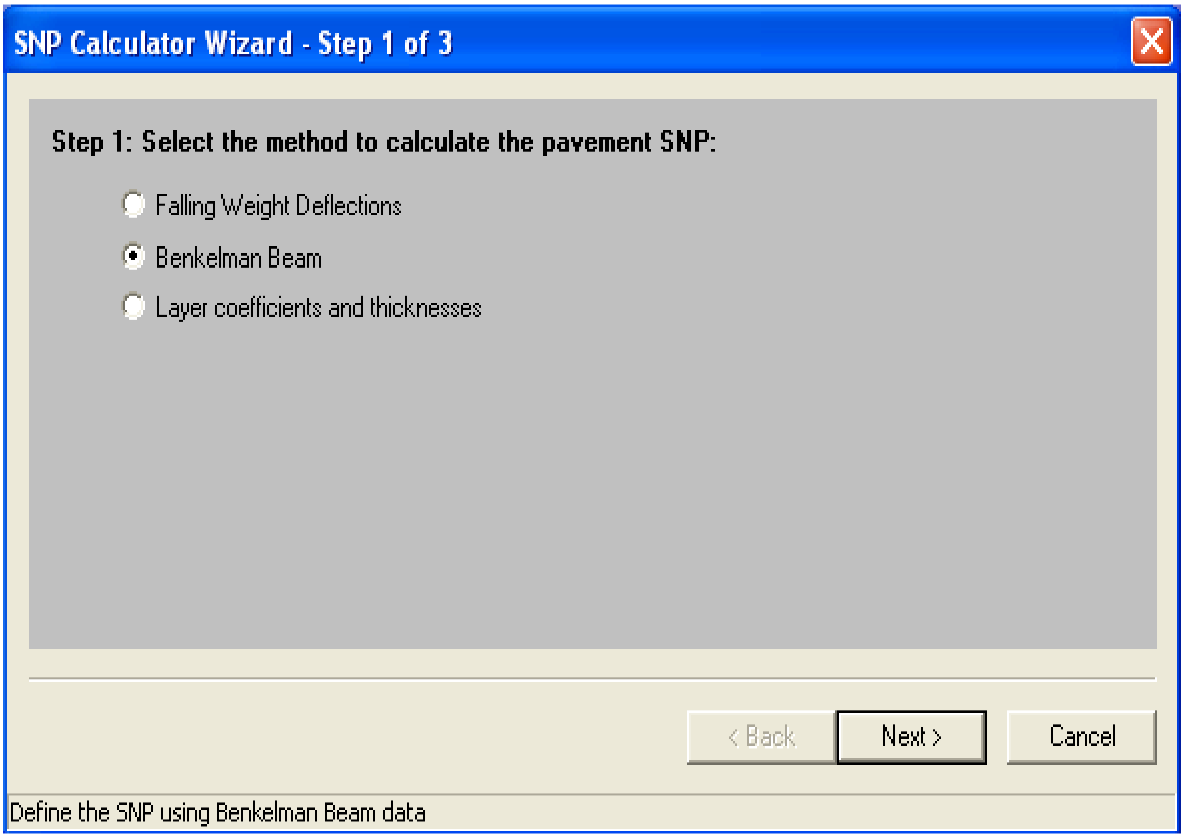


Fig. 4.6: SNP calculation using Benkelman Beam Data

4.3.2 Vehicle Fleet

For the study, Vehicle Fleet named as 'Patiala City Vehicle Fleet' has been created. Eight types of Motorized Vehicle (MT) *i.e.*, Two-wheeler, Car/Jeep/Van, Auto-Rickshaw, Bus (Medium), Mini-Bus, Truck, Mini-Truck and Tractor/Trolley and three types of Non-Motorized Vehicle (NMT) *i.e.*, Cycle, Man-Driven Rickshaw and Cart have been included in this vehicle fleet. All the vehicles with their basic characteristic data and economic unit costs (mentioned in previous chapter) are entered as inputs into vehicle attributes under vehicle fleet section in HDM-4 software. Snapshots of entering vehicle fleet data for Two-wheeler have been shown from Figs. 4.7-4.9. This vehicle fleet has been used further for determining the objectives of the present study.

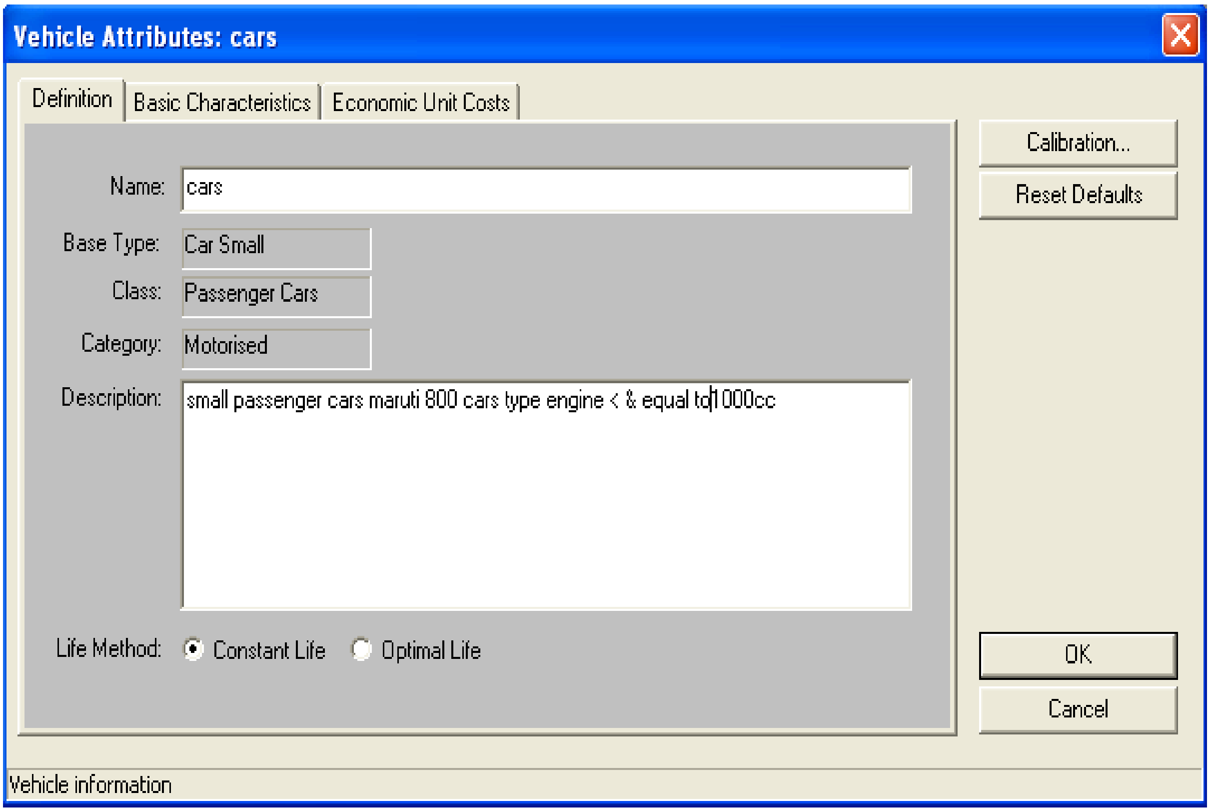


Fig. 4.7: Definition Data Input Entry for Car into Patiala City Vehicle Fleet

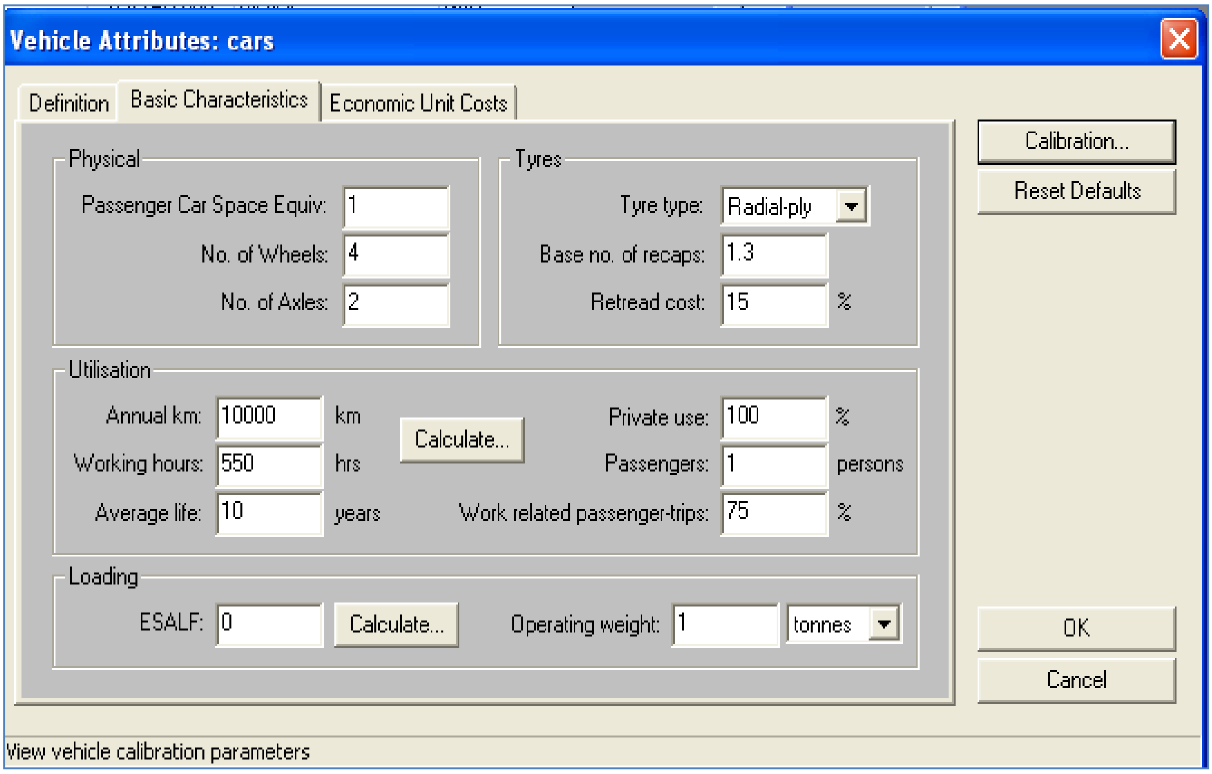


Fig. 4.8: Basic Characteristics Data Input Entry for Car

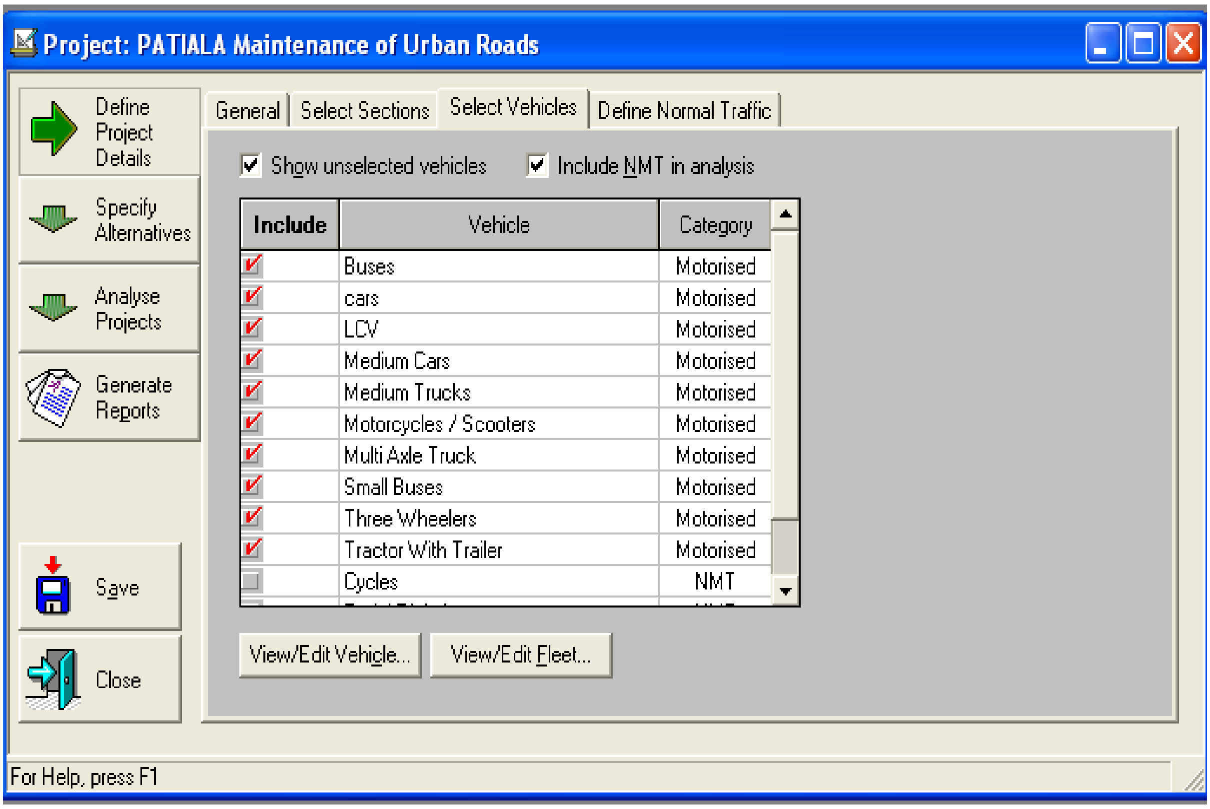


Fig. 4.9: Vehicle Fleet with all the Vehicles Defined

4.4 RSL OF ROAD SECTIONS

The aim of the very first objective was to compute RSL of each road section. RSL of a road section means the time period in years after which the reconstruction of the pavement is to be carried out by the agencies, providing no Maintenance and Rehabilitation (M&R) works throughout the intervening period (Gupta and Kumar, 2015). ‘Project Analysis’ in HDM-4 has been selected for determining this parameter.

4.4.1 Input Data

A new project named as ‘Determination of RSL’ was created which consisted of ‘Patiala City Road Network’ and ‘Patiala City Vehicle Fleet’ as inputs. The intervening period (analysis period) for the analysis of the project was taken as 10 years keeping in mind that all the selected road sections will require reconstruction work within next ten years when no maintenance work is provided during the intervening period. Analyze by project was chosen for analysis. Fig. 4.10 shows general input data for Project: RSL of pavements.

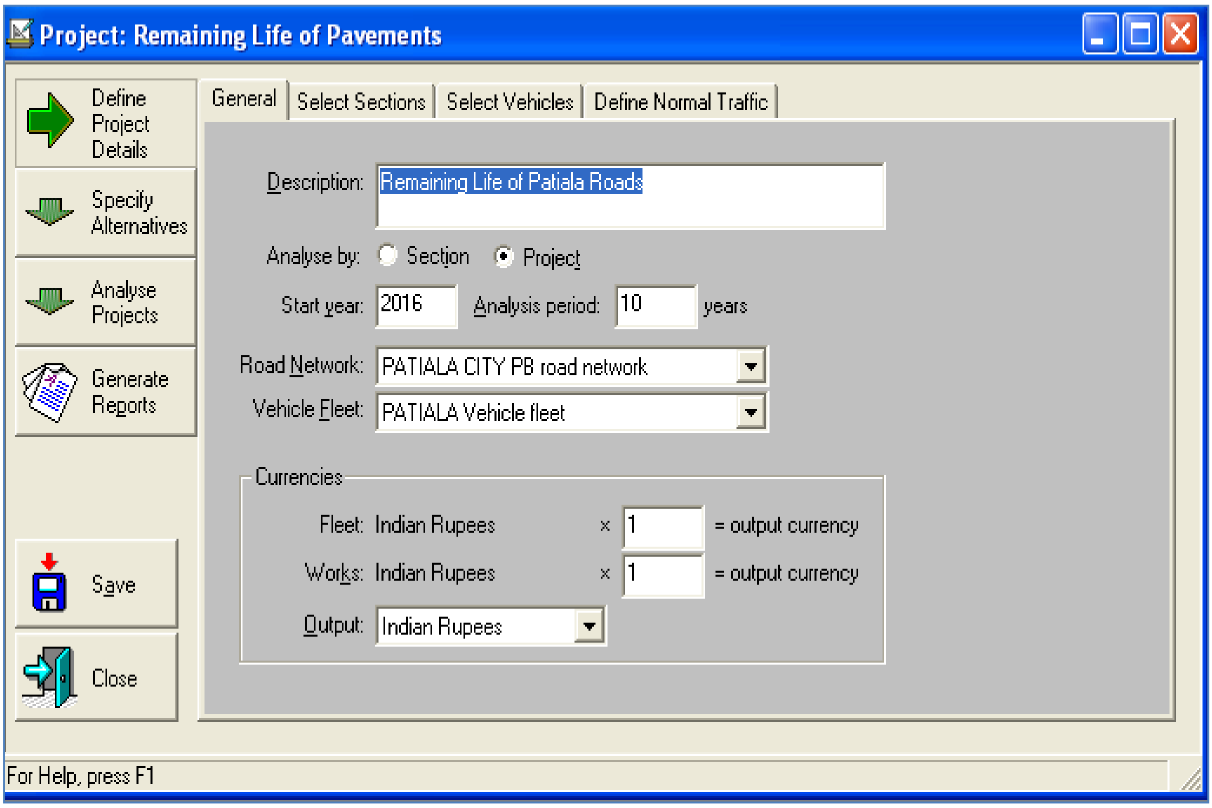


Fig. 4.10: General Input Data for Project: Determination of RSL

4.4.2 Selection of Sections and Vehicles

All the sixteen sections from Patiala City Road Network and all the types of vehicles from Patiala City Vehicle Fleet were selected for the analysis purpose.

4.4.3 Define Normal Traffic

Normal traffic details such as Vehicular compositions with their annual average growth rate for both MT and NMT vehicles have been inputted for each section.

4.4.4 Specify M&R Alternative

The condition responsive alternative named as ‘No maintenance till Reconstruction’ has been defined for the project in which ‘Reconstruction’ maintenance work standard was assigned along with intervention criteria to each road section. As road roughness plays a vital role in PMMS, Roughness >= 6 m/km IRI has been taken as intervention criteria for reconstruction work. Fig. 4.11-4.12 show the specification of M&R alternative.

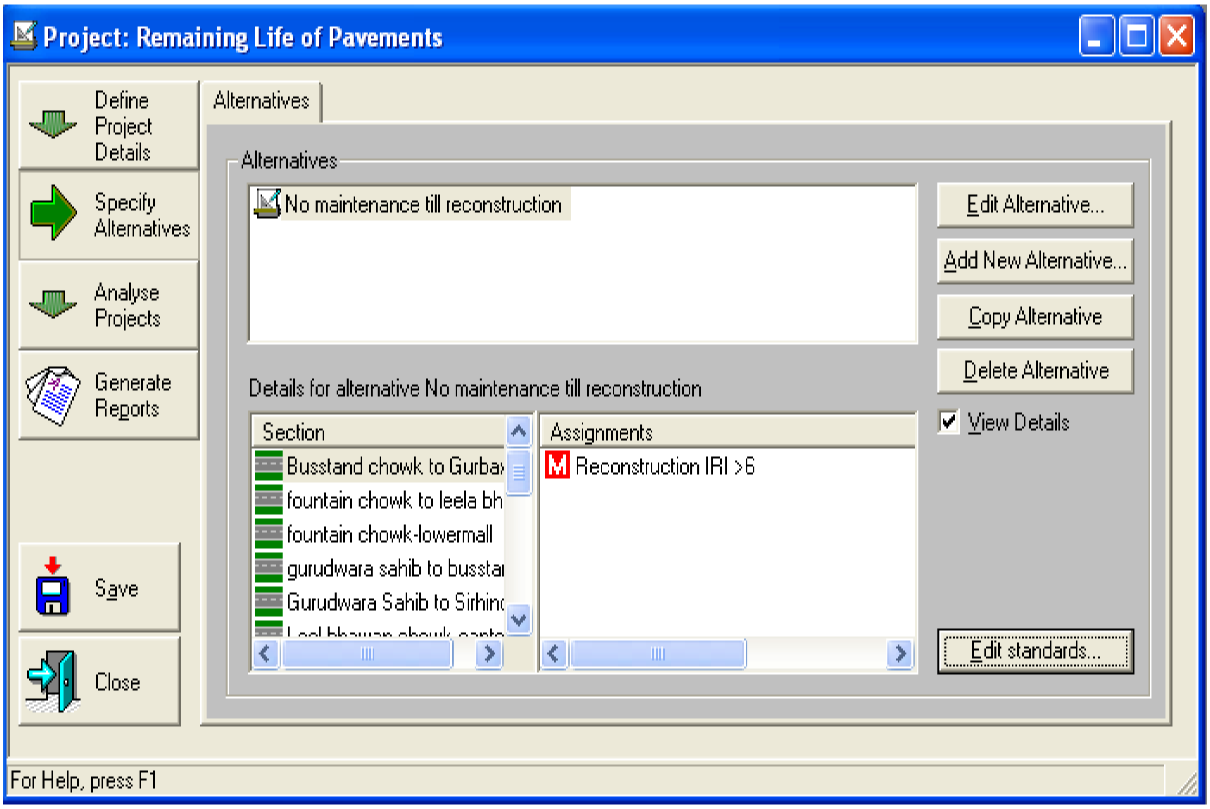


Fig. 4.11: Defined M&R Alternative for all Selected Pavement Sections

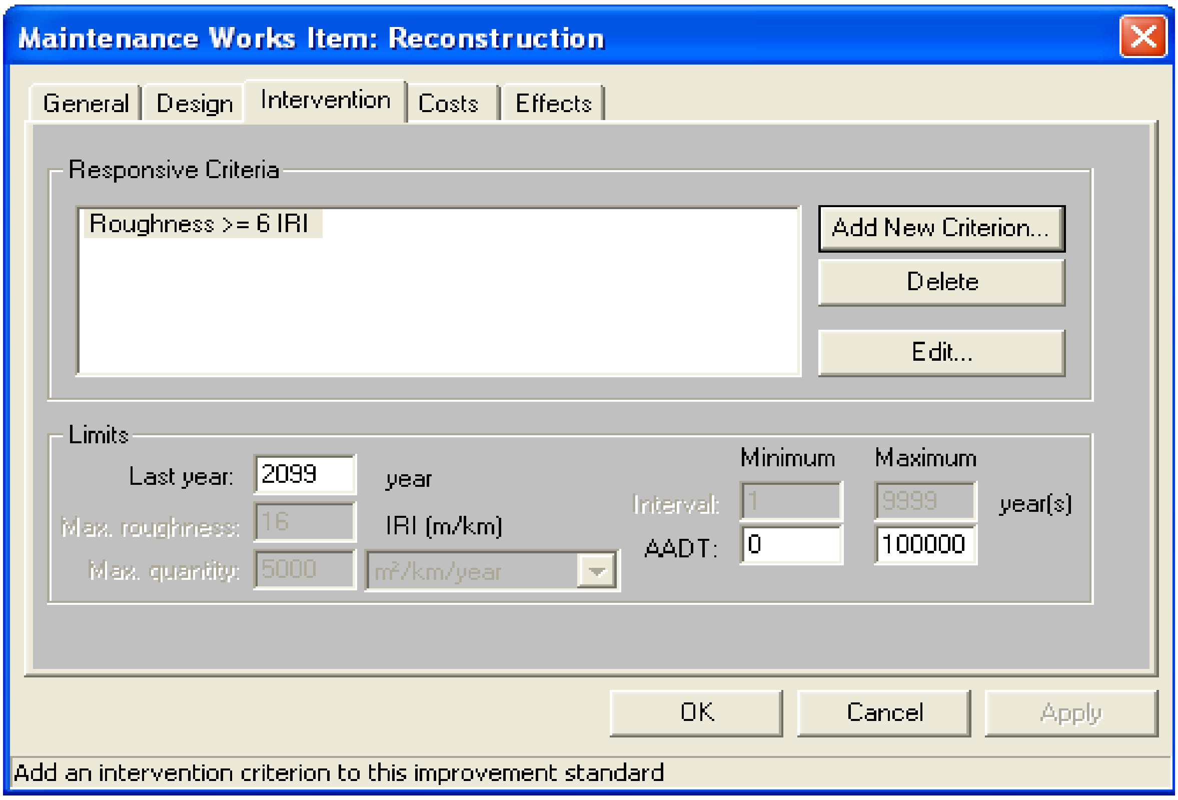


Fig. 4.12: Intervention Criteria for Selected M&R Work Item

4.4.5 Project Analysis

The project analysis application was run for analyzing the pavement future condition (pavement deterioration) of all the selected road sections under assigned M&R alternative. Fig. 4.13 shows the run analysis of the project.

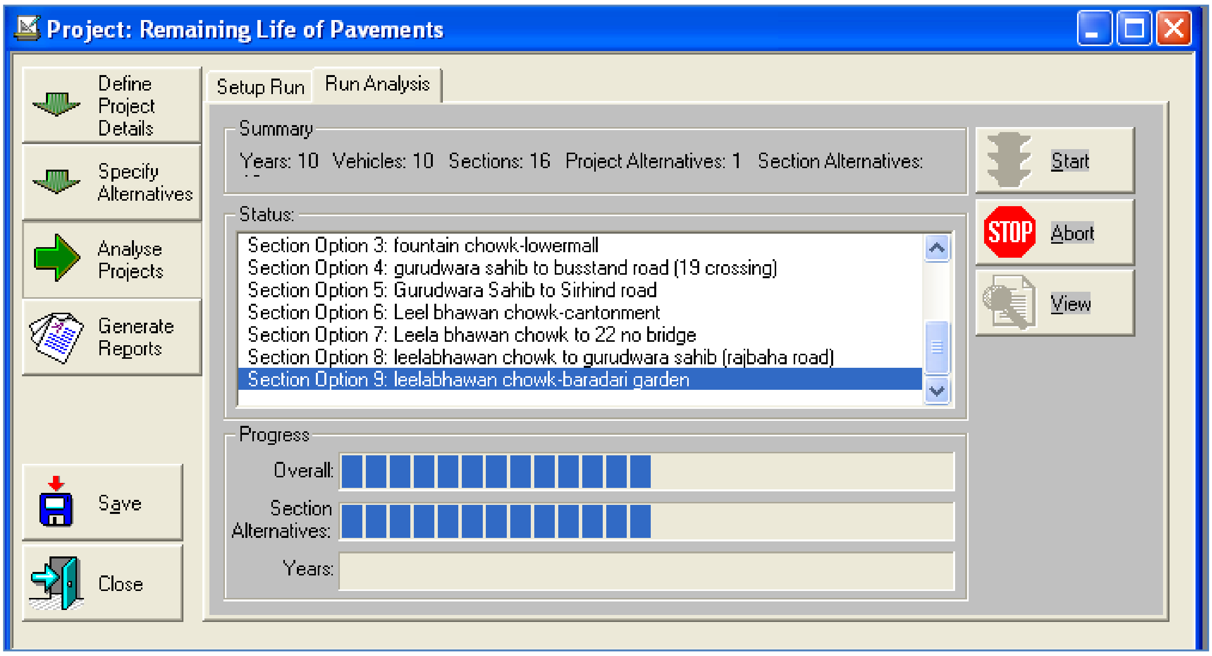


Fig. 4.13: Run Analysis of Project: RSL of Pavement

4.4.6 Roughness Progression

The Roughness progresses with each year (start year - 2016). If it exceeds intervention value *i.e.*, > = 6 IRI in a certain year, Reconstruction alternative shall be triggered for that year. Fig. 4.14- 4.15 show roughness progression graph for all the selected road sections. The sharp fall in average roughness values indicates the reconstruction work of the road section in that certain year.

4.4.7 Determination of Remaining Service Life (RSL)

RSL of all the pavements is the network is determined in terms of the number of years left before the reconstruction of the road surface is required based upon the condition responsive intervention criteria of roughness in terms of IRI. Reconstruction will be initiated till the roughness value of the surface progress till the intervention criteria of roughness. RSL of all the road sections were computed from the above mentioned roughness progression graphs and road work summary report of the road sections. Table 4.1 shows the computed RSL values of each road section. It can be observed from Fig. 4.16 that all the road sections will require reconstruction work within 0 to 9 years if no M&R work is assigned to the road sections throughout the intervening period.

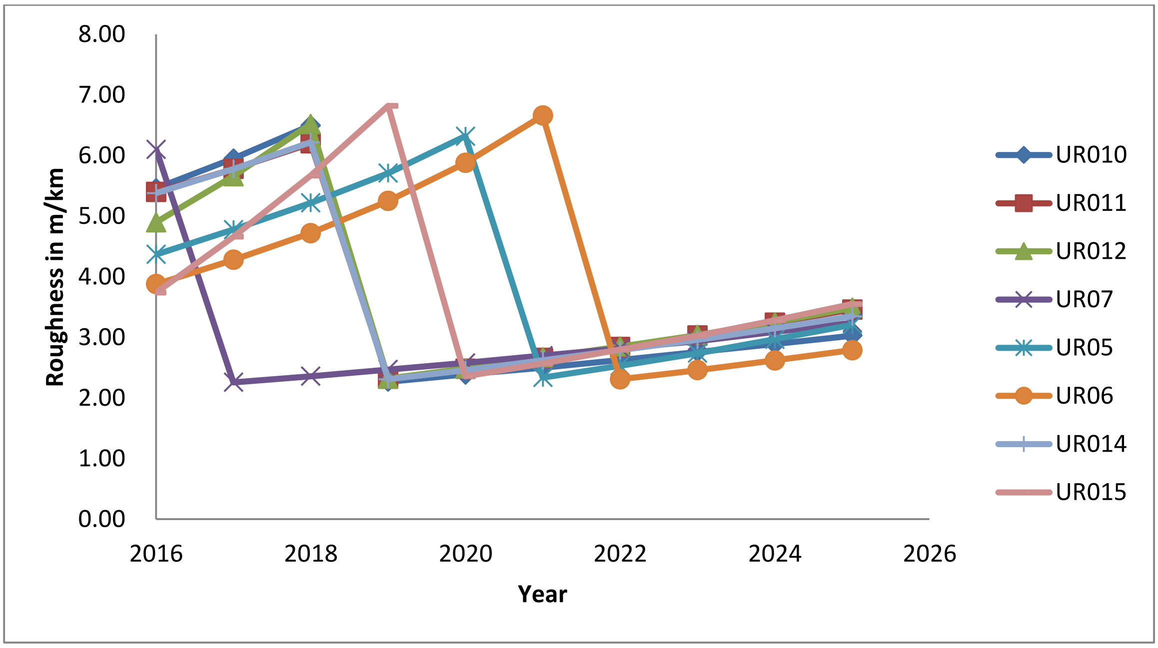


Fig. 4.14: Roughness Progression for various Road Sections

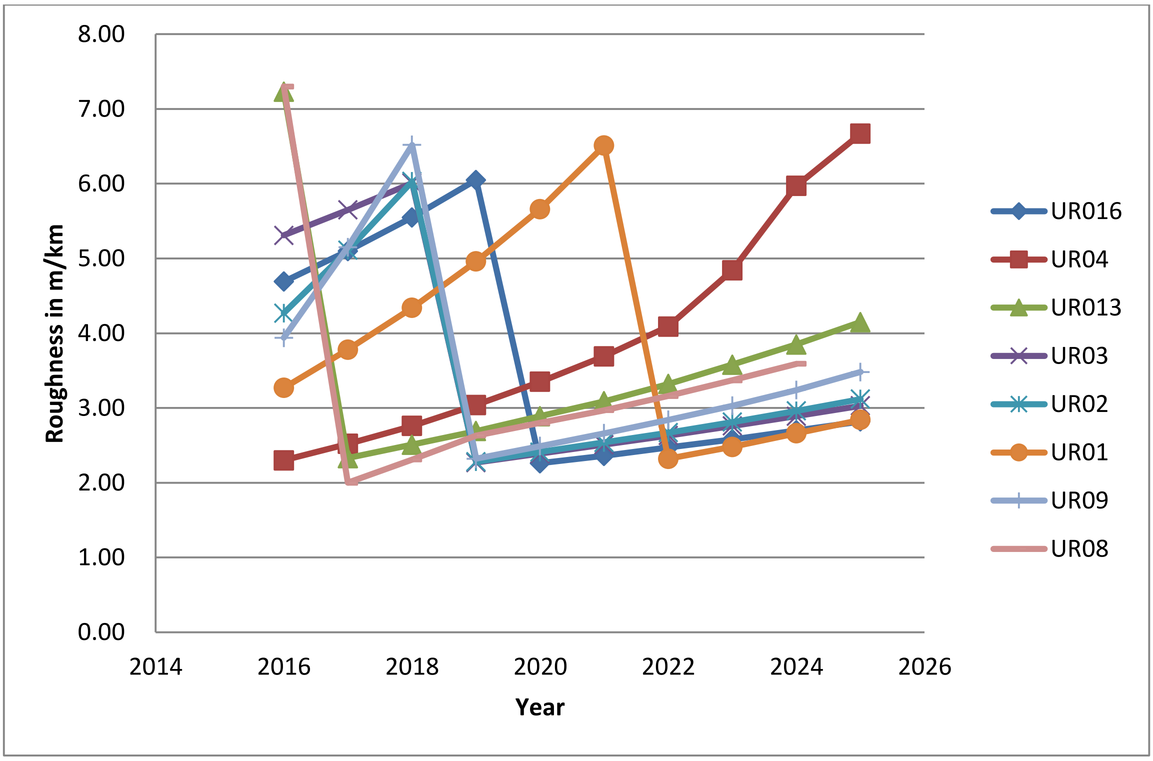


Fig. 4.15: Roughness Progression for various Road Sections

Table 4.1: RSL of Each Road Section

Section ID	Reconstruction Year	RSL (in years)
UR01	2021	5
UR02	2018	2
UR03	2018	2
UR04	2025	9
UR05	2020	4
UR06	2021	5
UR07	2016	0
UR08	2016	0
UR09	2018	2
UR010	2018	2
UR011	2018	2
UR012	2018	2
UR013	2016	0
UR014	2018	2
UR015	2019	3
UR016	2019	3

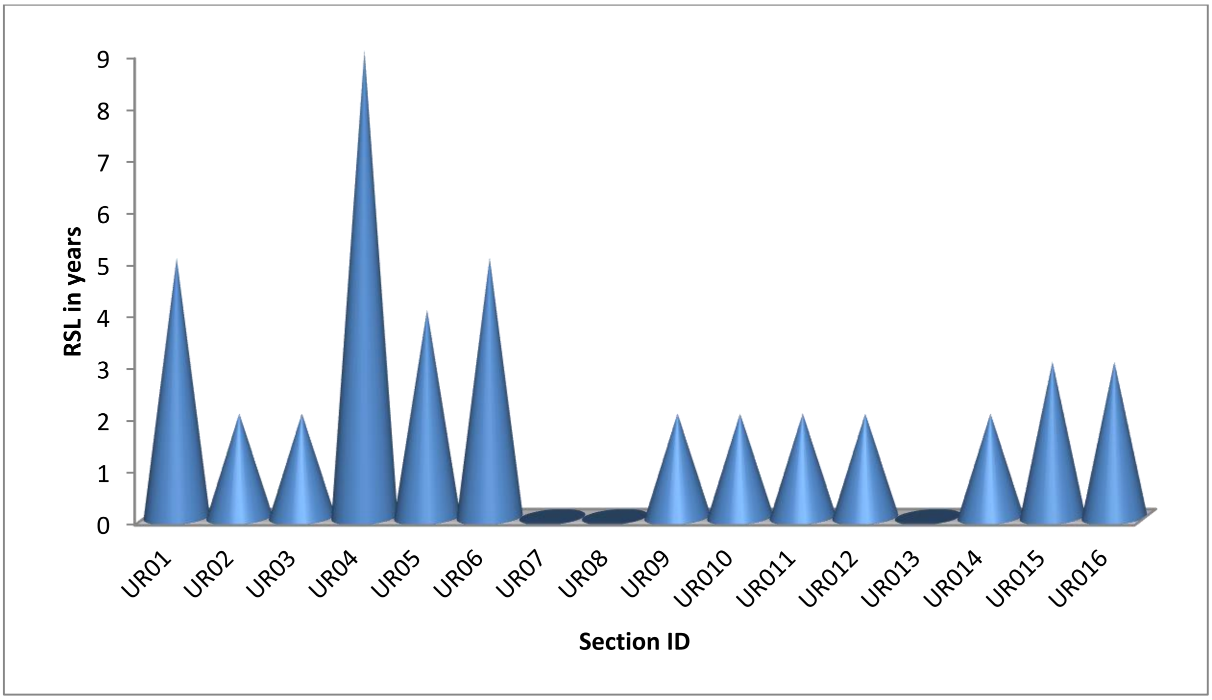


Fig. 4.16: RSL (in years) for various Road Sections

RSL value of the road section will help the road agency to know the imperative time for reconstruction work prior to the failure of entire road. Budgeting and funding for reconstruction work can be done accordingly.

4.5 DETERMINATION OF OPTIMUM M&R STRATEGY FOR ALL THE ROAD SECTIONS

The aim of this objective is to determine the optimum M&R strategy for all the sixteen road sections. The result shows the economic analysis of M&R strategies for road sections. The importance of this objective is to evaluate the cost-effective benefits resulting from investing in M&R works of a road section at the appropriate time, as compared against carrying out minimum routine maintenance annually. The optimum M&R strategy has been selected on the basis of economic indicators, such as NPV/Cost Ratio. Project Analysis in HDM-4 has been adopted for this objective.

4.5.1 Input Data

A new project named as 'Determination of Optimum M&R Strategy' was created which consisted of 'Patiala City Road Network' and 'Patiala City Vehicle Fleet' as inputs. Analysis period (intervening period for analysis of the project) was taken as 15 years.

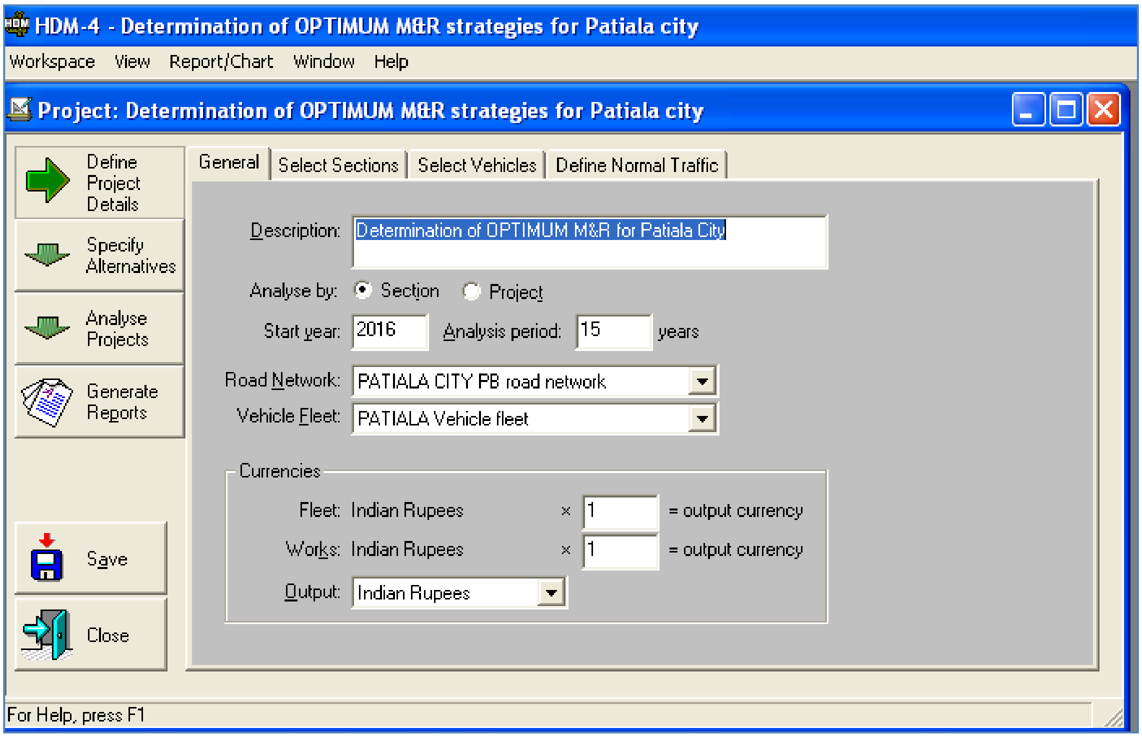


Fig. 4.17: General Data Input for Project to Determinate Optimum M&R Strategy

Analyze by section has been chosen. Input and output currencies are taken as Rupees. Fig. 4.17 shows general data input for Project to determinate of Optimum M&R Strategy.

4.5.2 Selection of Sections and Vehicles

In the present study, all the sixteen road sections have been selected from Patiala City Road Network. All the eleven types of vehicle have been marked and selected from 'Patiala City Vehicle Fleet' for the analysis of this project.

4.5.3 Define Normal Traffic

Normal traffic details such as 'Vehicular Compositions' with their annual average growth rate for both MT and NMT vehicles have been inputted for individual road section.

4.5.4 Proposed Maintenance and Rehabilitation (M&R) Alternatives

Four Maintenance and Rehabilitation (M&R) alternatives have been proposed for this objective and given in Table 4.2 (keeping in mind the serviceability level of sub-arterial & other roads).

Table 4.2: Proposed M&R Alternatives

M&R Strategy	Works Standard	Description of Work	Intervention Level
Base Alternative	Routine	Crack Sealing	>10%
		Patching	>10%
		Pothole repair	>3 No.
		Ravel repair	>10%
		Drain cleaning	Scheduled annually
Alternative1	Resealing	Provide 25 mm SBSD	Total damage area > 10% of total area
Alternative 2	Thin Overlay	Provide 25 mm SDBC overlay	Roughness >4 m/km IRI
Alternative 3	Thick Overlay	Provide 30 mm BC overlay	Roughness >4 m/km IRI
Alternative 4	Resealing + Overlay	Provide 25 mm SBSD + overlay of 30 mm BC	Total damage area > 10% of total area, and Roughness > 4 m/km

			IRI
Alternative 5	Reconstruction	Provide (50 mm Dense Bituminous Macadam + 30 mm Bituminous Concrete)	Roughness > 6 m/km IRI and Carriageway cracked area > 15% of total area

Note: IRI-International Roughness Index, SBSD – Single Bituminous Surface Dressing, SDBC – Semi Dense Bituminous Concrete, BC – Bituminous Concrete, DBM – Dense Graded Bituminous Macadam.

4.5.5 Specify M&R Alternatives

Proposed M&R alternatives have been specified in the project. Corresponding to these alternatives, M&R work items with their economic costs have been assigned with the required intervention levels. Fig. 4.18 shows all the proposed M&R alternatives for analysis of this project. Fig. 4.19 shows work items assigned for ‘Routine Work Standard'. Fig. 4.20-4.32 show the data input for 'Patching' work item.

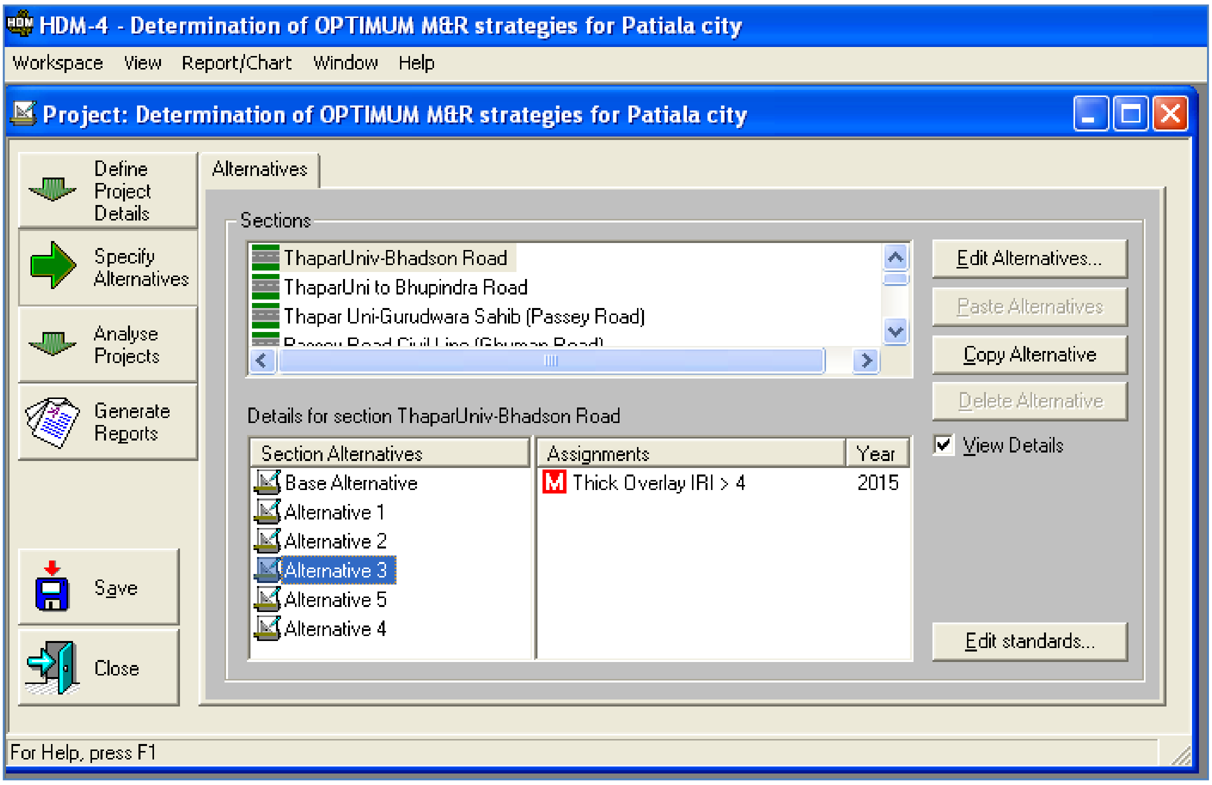


Fig. 4.18: Proposed M&R Alternatives for Project Analysis of various road sections

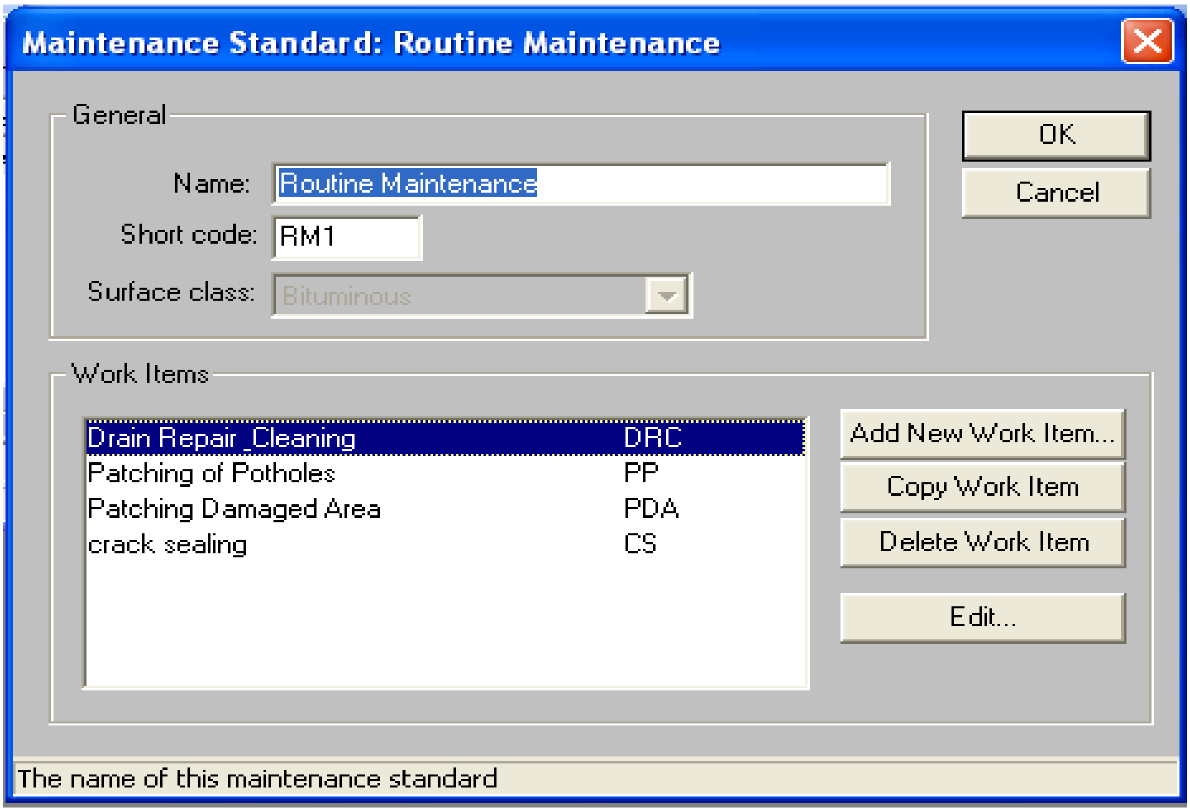


Fig. 4.19: Work Items Assigned for 'Routine' Work Standard

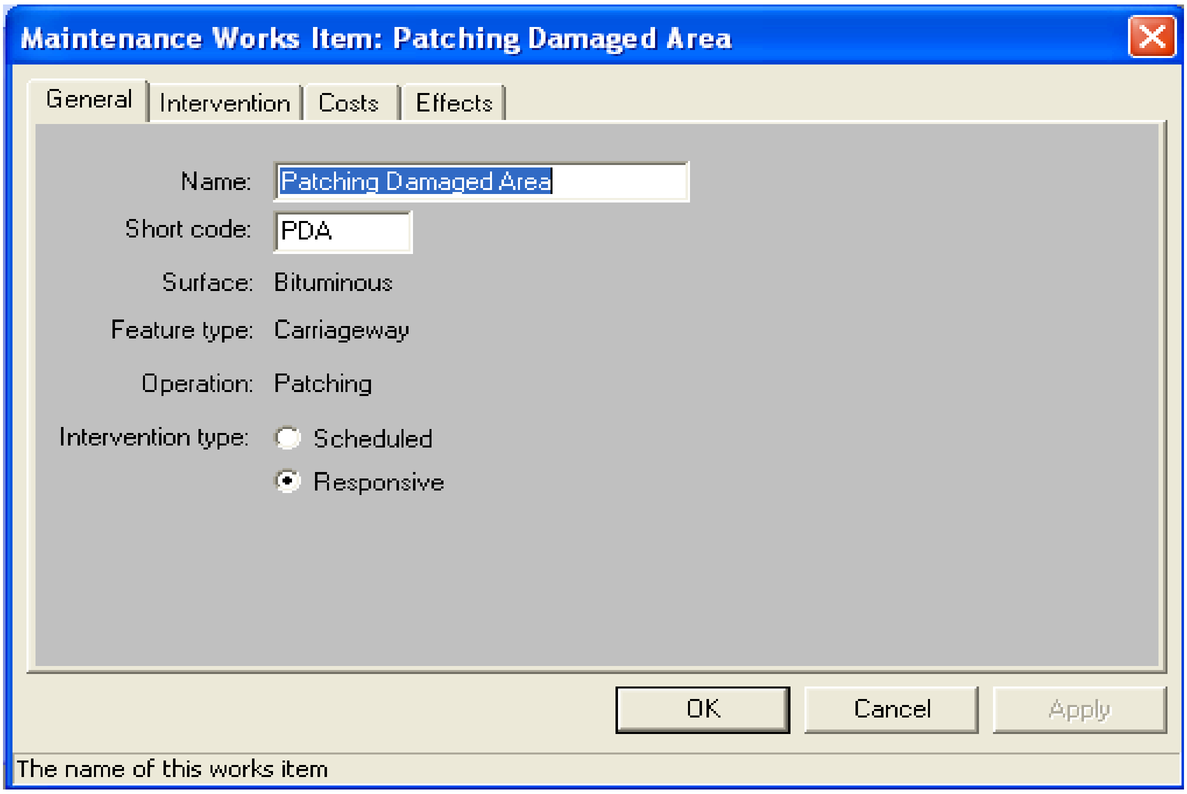


Fig. 4.20: General Input Data for 'Patching Damaged Area' Work Item

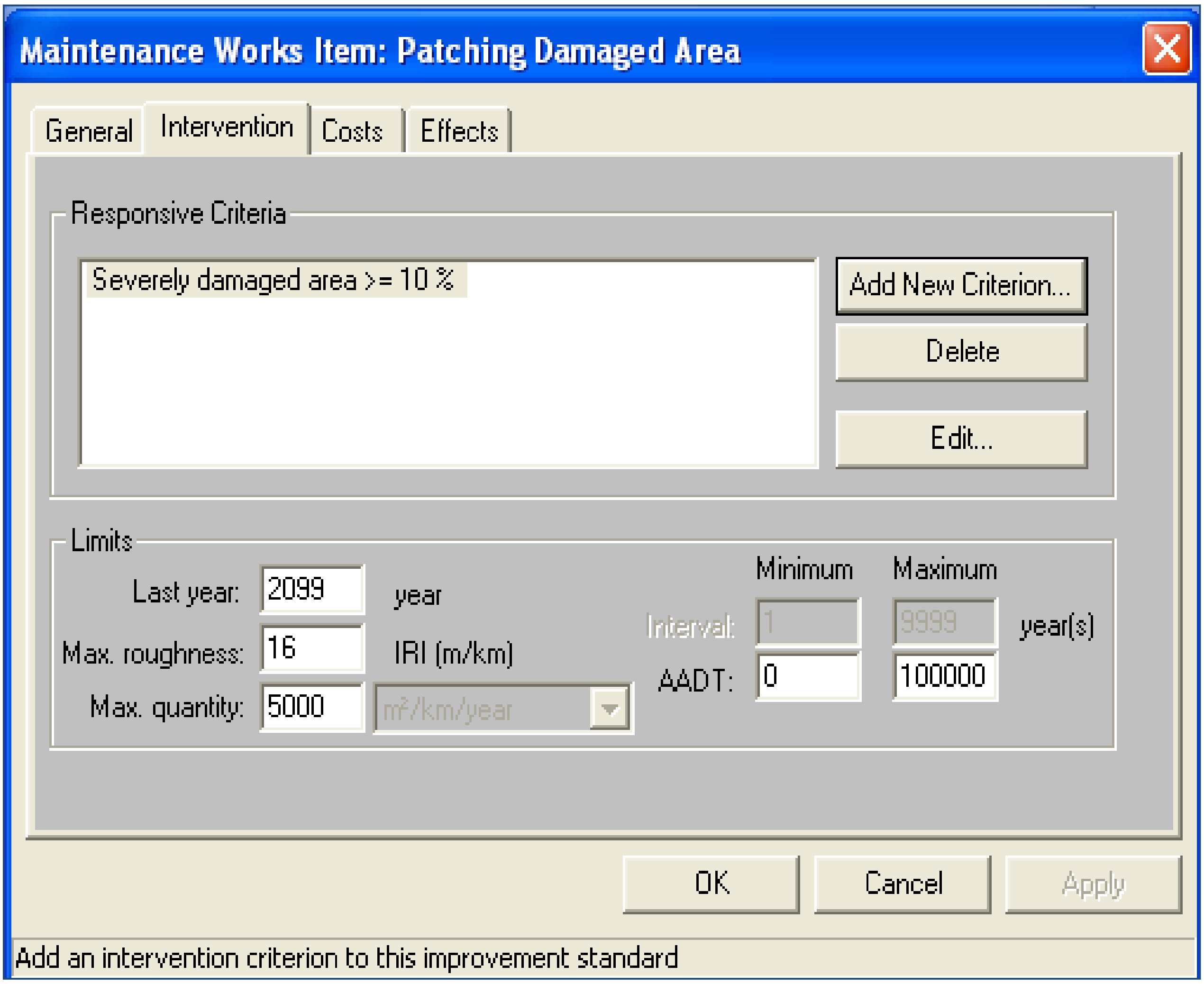


Fig. 4.21: Intervention criteria for 'Patching Damaged Area' Work Item

4.5.6 Project Analysis

As the economic analysis for the selected sections has to be done, so in Set-up Run of Project Analysis, 'Conduct Economic Analysis' has been selected. Base Alternative has selected for comparison purpose by default. A discount rate of 12 % was taken as shown in Fig. 4.22. The choice of discount rate is governed by various factors such as future availability of finance, various opportunities for its use *etc*. A discount rate of 12 % can be taken for economic analysis in developing country like India (Clause 7.8, IRC: SP: 30-2009).

Project Run Analysis has been carried for all the selected road sections. As a result of this analysis, the road pavement deterioration/works reports and M&R works reports have been generated corresponding to each M&R alternative considered above.

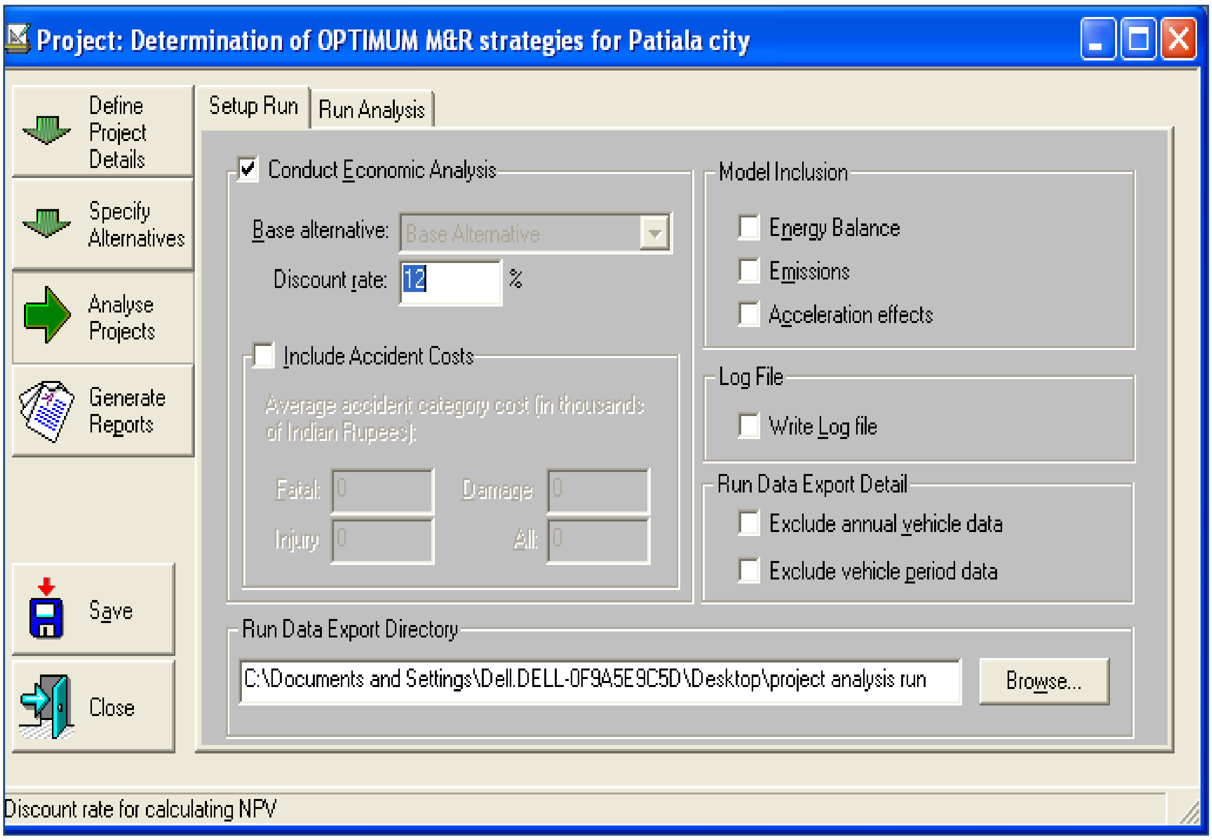


Fig. 4.22: Set-up Run for Project Analysis

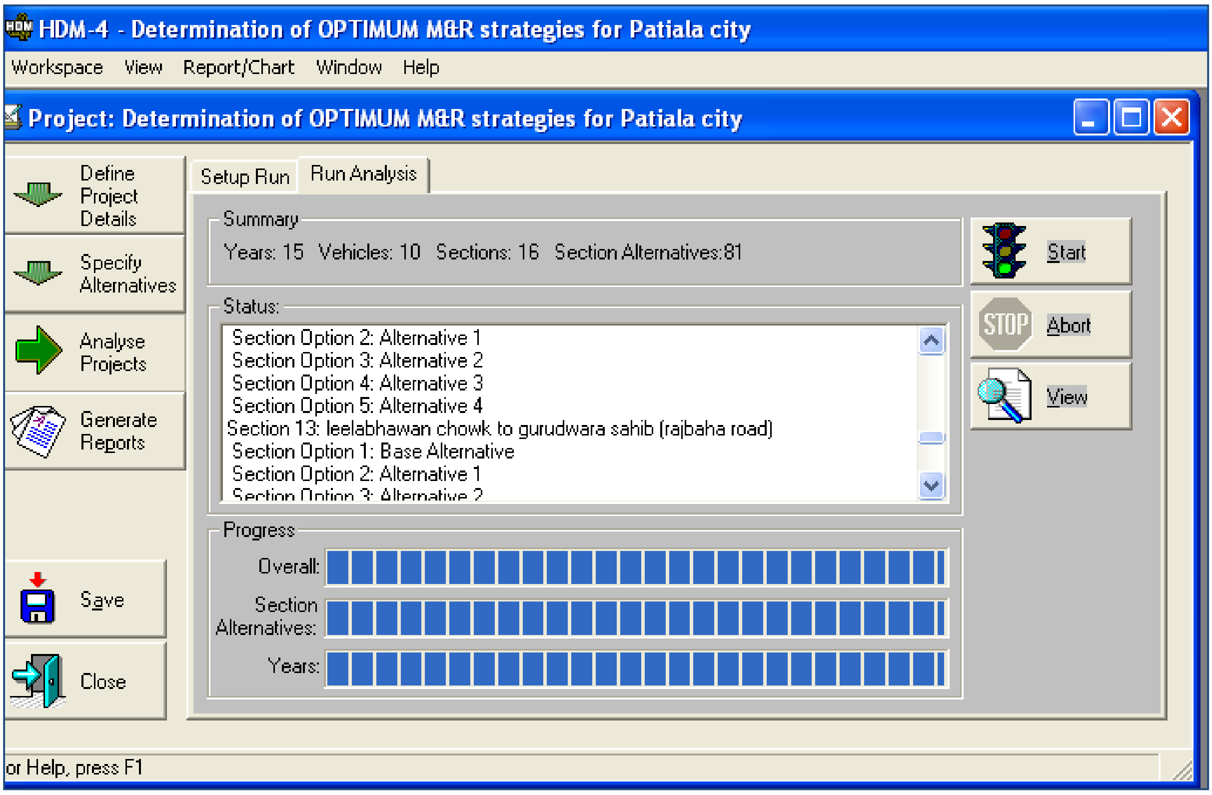


Fig. 4.23: Run analysis for Project to determine Optimum M&R Strategies

4.5.7 Road Pavement Deterioration

The pavement deterioration summary reports of various road sections, as obtained under proposed M&R strategies over the analysis period of 15 years, has been considered from output of HDM-4 analysis. The Roughness progression graphs of all the alternatives for the road sections UR010, UR012, UR015 & UR013 are shown individually from Figs. 4.24 - 4.27. The intervention criteria for various alternatives have been successfully implemented as predicted from the roughness progression values and the drop in the roughness value as soon as the maintenance alternative has been provided.

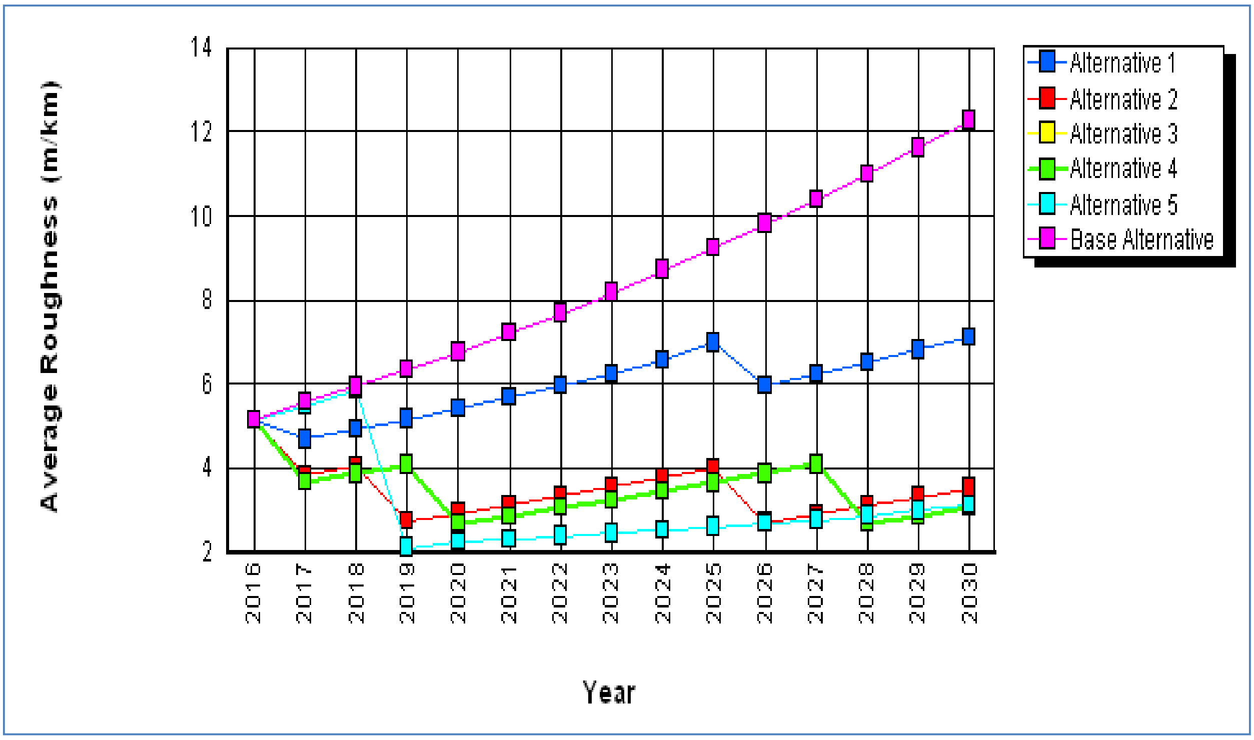


Fig. 4.24: Roughness Progressions under All Alternatives for UR010

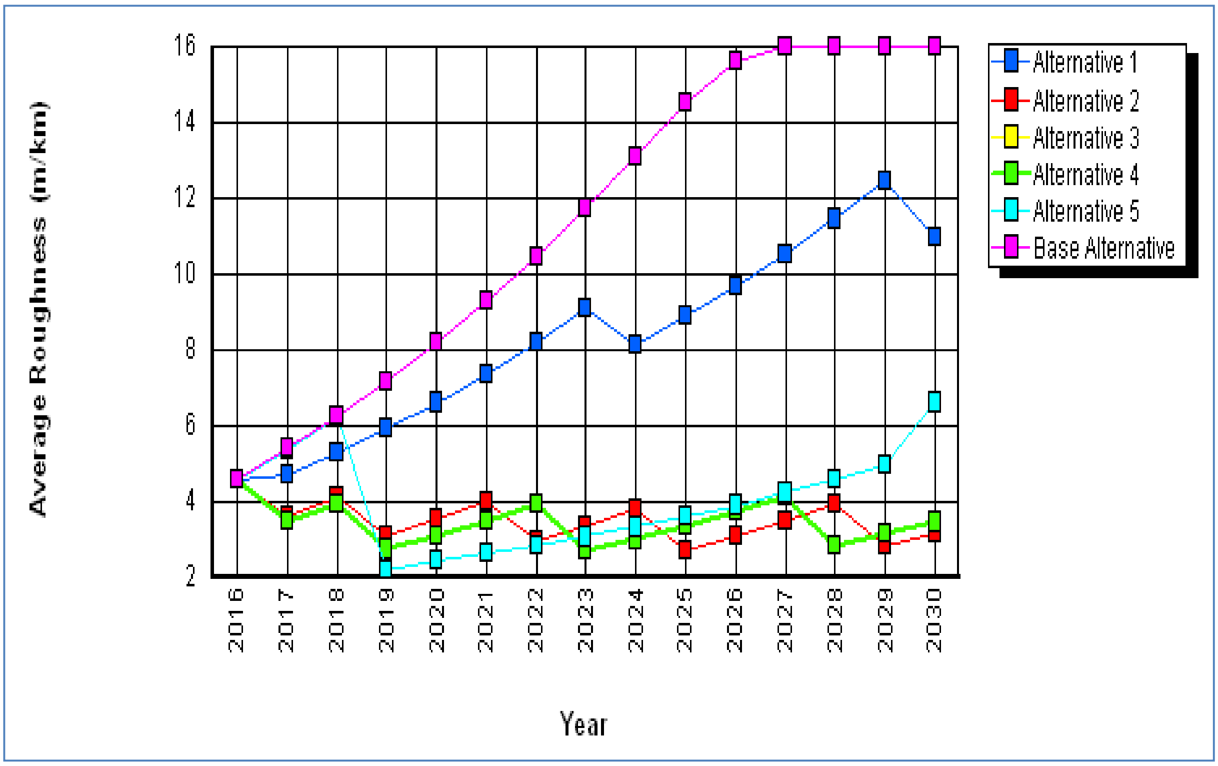


Fig. 4.25: Roughness Progressions under all Alternatives for UR012

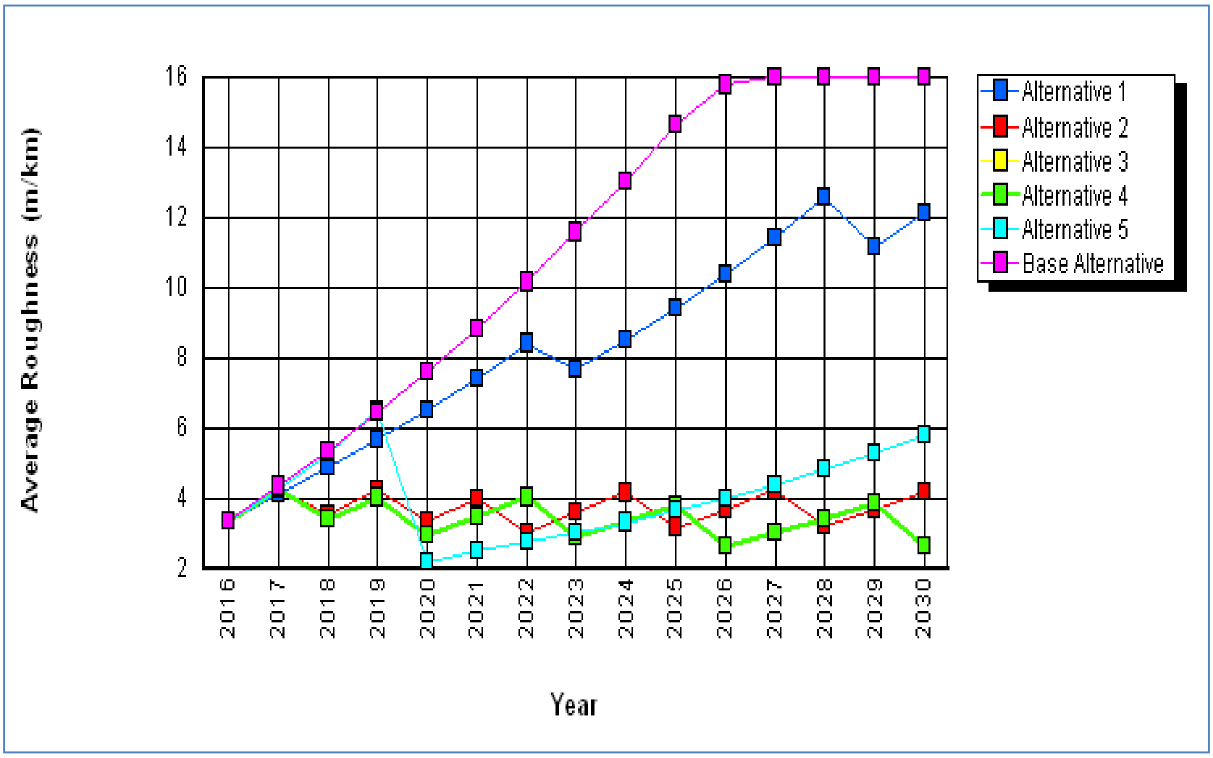


Fig. 4.26: Roughness Progressions under all Alternatives for UR015

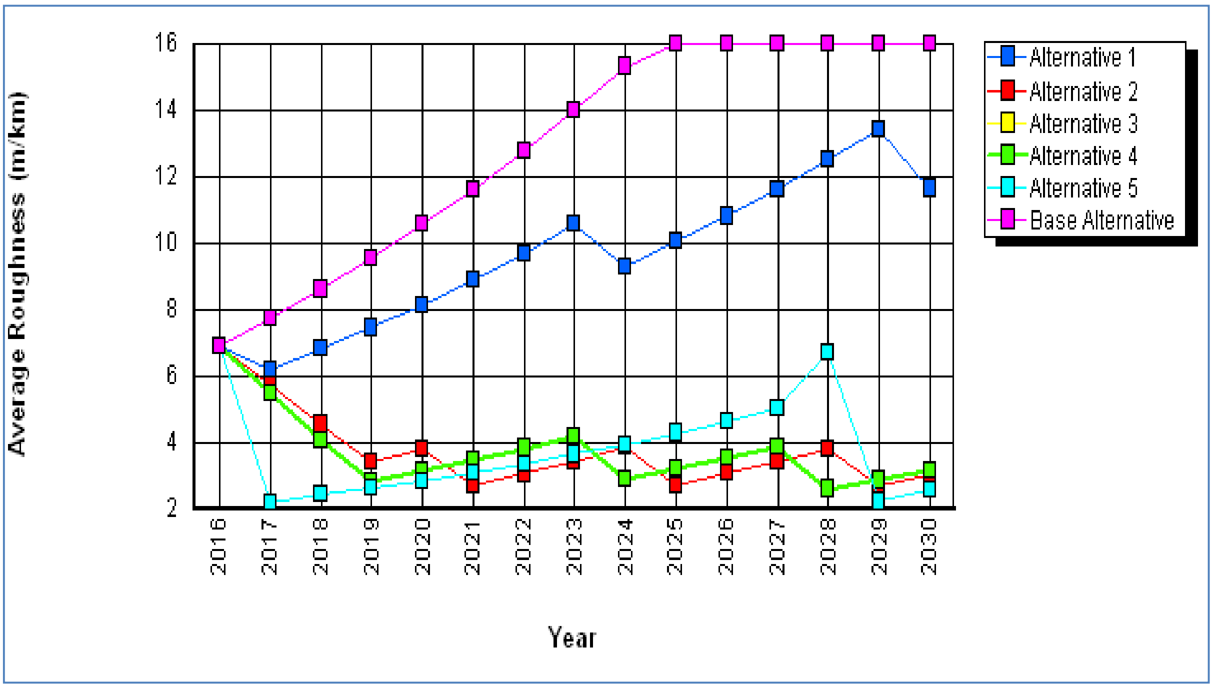


Fig. 4.27: Roughness Progressions under all Alternatives for UR013

4.5.8 M&R Works Report

The various works resulting from application of all the specified M&R strategies (as triggered by the respective intervention parameters), timings of their application and associated cost of each work item are given in the M&R works report of road sections UR010, UR012 & UR015 from Tables 4.3 - 4.8. This works report gives description of the works that would be implemented in each year of the analysis period under each M&R strategy.

Table 4.3: M&R Works for UR010 during Analysis Period

Year	**M&R Works**					
	Base Alternative	**Alternative 1**	**Alternative 2**	**Alternative 3**	**Alternative 4**	**Alternative 5**
2016	Drain repair & cleaning, patching damaged area (DRC &	Implemented	Implemented	Implemented	Implemented	****

	PDA)					
2017	DRC & PDA	****	****	****	****	****
2018	DRC & PDA	****	Implemented	****	****	Implemented
2019	DRC & PDA	****	****	Implemented	Implemented	****
2020	DRC & PDA	****	****	****	****	****
2021	DRC & PDA	****	****	****	****	****
2022	DRC & PDA	****	****	****	****	****
2023	DRC & PDA	****	****	****	****	****
2024	DRC & PDA	****	****	****	****	****
2025	DRC & PDA	Implemented	Implemented	****	****	****
2026	DRC & PDA	****	****	****	****	****
2027	DRC & PDA	****	****	Implemented	Implemented	****
2028	DRC & PDA	****	****	****	****	****
2029	DRC & PDA	****	****	****	****	****
2030	DRC & PDA	****	****	****	****	****

**** means no M&R work assigned in the certain year

Table 4.4: Economic Costs of M&R Works for UR010

Alternative option	**Year of Implementation**	**Economic Cost (Rs)**
Base Alternative	2016 to 2030	1,876,227.50

Alternative 1	2016, 2025	3,835,365.50
Alternative 2	2016, 2018, 2025	9,009,099.70
Alternative 3	2016, 2019, 2027	14,332,600.40
Alternative 4	2016, 2019, 2027	14,332,600.40
Alternative 5	2018	10,646,999.00

Table 4.5: M&R Works for UR012 throughout Analysis Period

Year	M&R Works					
	Base Alternative	**Alternative 1**	**Alternative 2**	**Alternative 3**	**Alternative 4**	**Alternative 5**
2016	Drain repair & cleaning, patching damaged area (DRC & PDA)	Implemented	Implemented	Implemented	Implemented	****
2017	DRC & PDA	****	Implemented	****	****	****
2018	DRC & PDA	****	****	Implemented	Implemented	Implemented
2019	DRC & PDA	****	****	****	****	****
2020	DRC & PDA	****	****	****	****	****
2021	DRC & PDA	****	****	****	****	****
2022	DRC & PDA	****	****	****	****	****
2023	DRC & PDA	Implemented	Implemented	****	****	****
2024	DRC &	****	****	Implemente	Implemente	****

	PDA			d	d	
2025	DRC & PDA	****	****	****	****	****
2026	DRC & PDA	****	****	****	****	****
2027	DRC & PDA	Implemented	****	****	****	****
2028	DRC & PDA	****	****	****	****	****
2029	DRC & PDA	****	Implemented	****	****	****
2030	DRC & PDA	****	****	****	****	Implemented

**** means no M&R work assigned in the certain year

Table 4.6: Economic Costs of M&R Works for UR012

Alternative option	**Year of Implementation**	**Economic Cost (Rs)**
Base Alternative	2016 to 2030	1,090,289.10
Alternative 1	2016, 2023, 2027	3,675,068.40
Alternative 2	2016, 2017, 2023, 2029	7,700,068.40
Alternative 3	2016, 2018, 2024	9,187,568.40
Alternative 4	2016, 2018, 2024	9,187,568.40
Alternative 5	2018, 2030	13,649,999.00

Table 4.7: M&R Works for UR015 throughout Analysis Period

Year	**M&R Works**					
	Base Alternative	**Alternative 1**	**Alternative 2**	**Alternative 3**	**Alternative 4**	**Alternative 5**
2016	Drain repair & cleaning, patching	Implemented	****	****	****	****

	damaged area (DRC & PDA)					
2017	DRC & PDA	****	Implemented	Implemented	Implemented	****
2018	DRC & PDA	****	****	****	****	****
2019	DRC & PDA	****	Implemented	Implemented	Implemented	Implemented
2020	DRC & PDA	****	****	****	****	****
2021	DRC & PDA	****	Implemented	****	****	Implemented
2022	DRC & PDA	Implemented	****	Implemented	Implemented	****
2023	DRC & PDA	****	****	****	****	****
2024	DRC & PDA	****	Implemented	****	****	****
2025	DRC & PDA	****	****	Implemented	Implemented	****
2026	DRC & PDA	****	****	****	****	****
2027	DRC & PDA	****	Implemented	****	****	****
2028	DRC & PDA	Implemented	****	****	****	****
2029	DRC & PDA	****	****	Implemented	Implemented	****
2030	DRC & PDA	****	Implemented	****	****	Implemented

**** means no M&R work assigned in the certain year

Table 4.8: Economic Costs of M&R Works for UR015

Alternative option	**Year of Implementation**	**Economic Cost (Rs)**
Base Alternative	2016 to 2030	3,955,238.00
Alternative 1	2016, 2022, 2028	7,668,895.90
Alternative 2	2017, 2019, 2021, 2024, 2027, 2030	24,090,081.00
Alternative 3	2017, 2019, 2022, 2025, 2029	31,937,581.00
Alternative 4	2017, 2019, 2022, 2025, 2029	31,937,581.00
Alternative 5	2019, 2030	28,470,000.00

4.5.9 Economic Analysis of M&R Strategy

Selection of optimum M&R strategy by economic analysis is based on any of the economic indicators *i.e.*, Net Present Value/Capital Cost (NPV/CAP) Ratio, Internal Rate of Return (IRR) or Net Benefits. In this study, economic indicator NPV/CAP ratio has been considered for selection of optimum M&R strategy for all the road sections. The summaries of economic analysis for all the road sections has been given in Table 4.9 and also represented in Fig. 4.28.

Table 4.9: Summary of Economic Analysis for Patiala Urban Road Network

Section ID	**Base Alternative NPV/CAP**	**ALT 1 NPV/CAP**	**ALT 2 NPV/CAP**	**ALT 3 NPV/CAP**	**ALT 4 NPV/CAP**	**ALT 5 NPV/CAP**
UR01	0.000	8.797	**9.369**	6.837	6.837	8.170
UR02	0.000	5.091	**7.010**	3.497	3.497	5.303
UR03	0.000	**4.888**	3.461	1.972	1.972	2.346
UR04	0.000	0.234	**0.459**	0.081	0.081	0.005
UR05	0.000	13.024	**13.116**	9.358	9.358	7.161
UR06	0.000	4.253	**5.854**	3.575	3.575	4.225
UR07	0.000	**16.051**	8.337	5.757	5.757	7.467
UR08	0.000	**24.541**	14.670	10.404	10.404	16.133
UR09	0.000	**11.833**	9.556	6.818	6.818	10.447

UR010	0.000	**6.207**	4.007	2.376	2.376	2.800
UR011	0.000	5.463	**6.993**	3.772	3.772	3.140
UR012	0.000	**11.533**	8.889	6.310	6.310	6.840
UR013	0.000	**21.630**	13.359	9.531	9.531	11.921
UR014	0.000	**9.801**	7.024	4.808	4.808	5.562
UR015	0.000	**11.126**	9.195	6.481	6.481	8.075
UR016	0.000	**3.573**	2.872	1.560	1.560	1.881

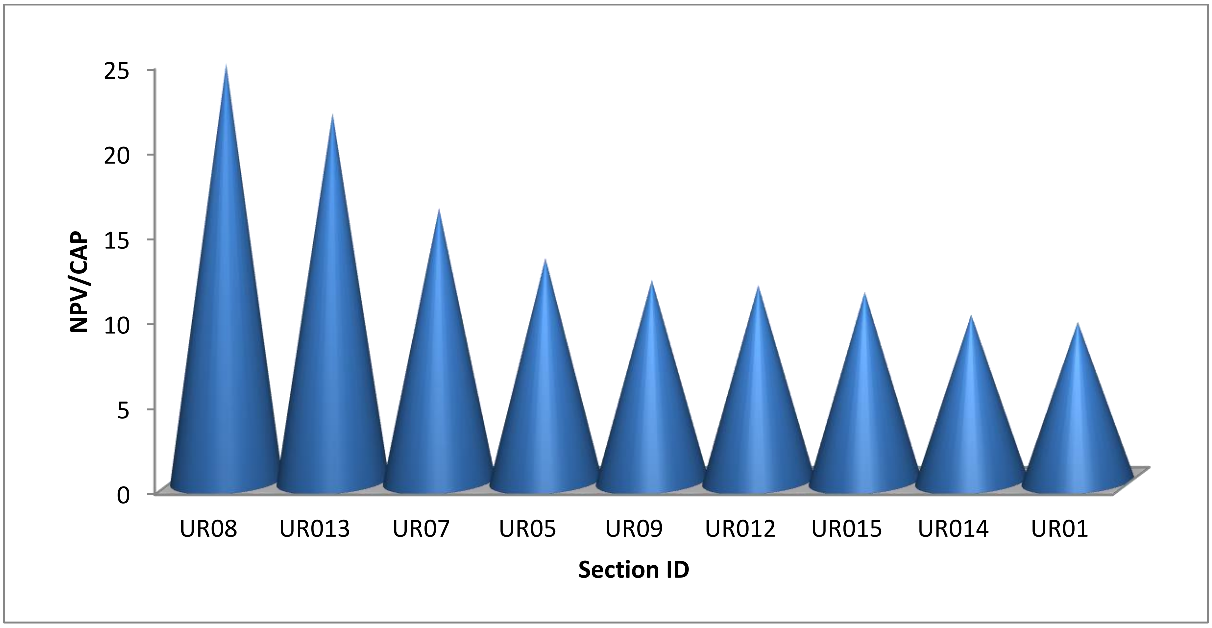


Fig. 4.28: NPV/CAP Ratio for various Road Sections

On the basis of economic analysis of each alternative for all the road sections, optimum M&R strategy or alternative has been selected. The alternative which has higher NPV/Cost ratio for any road section compared to the other predefined alternatives, is selected as optimum M&R strategy for that section. Table 4.10 incorporates the optimum M&R alternative selected for each road section.

Table 4.10: Optimum M&R Alternative for each Road Section

Section ID	**Optimum M&R Strategy**
UR01	Alternative 2 (Thin overlay of 25 mm SDBC)
UR02	Alternative 2 (Thin overlay of 25 mm SDBC)
UR03	Alternative 1 (Resealing, provide with 25 mm SBSD)

UR04	Alternative 2 (Thin overlay of 25 mm SDBC)
UR05	Alternative 2 (Thin overlay of 25 mm SDBC)
UR06	Alternative 2 (Thin overlay of 25 mm SDBC)
UR07	Alternative 1 (Resealing, provide with 25 mm SBSD)
UR08	Alternative 1 (Resealing, provide with 25 mm SBSD)
UR09	Alternative 1 (Resealing, provide with 25 mm SBSD)
UR010	Alternative 1 (Resealing, provide with 25 mm SBSD)
UR011	Alternative 2 (Thin overlay of 25 mm SDBC)
UR012	Alternative 1 (Resealing, provide with 25 mm SBSD)
UR013	Alternative 1 (Resealing, provide with 25 mm SBSD)
UR014	Alternative 1 (Resealing, provide with 25 mm SBSD)
UR015	Alternative 1 (Resealing, provide with 25 mm SBSD)
UR016	Alternative 1 (Resealing, provide with 25 mm SBSD)

On the basis of the economic analysis summary the optimum M&R strategy selected for sections UR03, UR07, UR08, UR09, UR010, UR012, UR013, UR014, UR015, UR016 is Alternative 1 (Resealing 25 mm SBSD) and for all other sections Alternative 2 (Thin overlay 25 mm SDBC) has been the optimum maintenance strategy with maximum NPV/CAP value.

4.5.10 Prioritization of Road Sections based on Optimum M&R Strategy

Based on optimum M&R strategy of the road sections, prioritization of all the road sections has been done. Higher the NPV/Cost ratio of optimum M&R strategy of the road section, higher will be the prioritization ranking of that road. Table 4.11 shows the prioritization ranking of road sections based on optimum M&R strategy and it can be observed that UR08 having top priority; UR04 with least priority with alterative 1 and alternative 2, respectively. The graphical representation of prioritization ranking has been presented in Fig. 4.29.

Table 4.11: Prioritization Ranking of the Road Section

Section ID	Optimum M&R Strategy	NPV/Cost Ratio	Prioritization Ranking
UR01	Alternative 2 (Thin overlay of 25 mm SDBC)	9.369	9
UR02	Alternative 2	7.01	10

	(Thin overlay of 25 mm SDBC)		
UR03	Alternative 1 (Resealing, provide with 25 mm SBSD)	4.888	14
UR04	Alternative 2 (Thin overlay of 25 mm SDBC)	0.459	16
UR05	Alternative 2 (Thin overlay of 25 mm SDBC)	13.116	4
UR06	Alternative 2 (Thin overlay of 25 mm SDBC)	5.854	13
UR07	Alternative 1 (Resealing, provide with 25 mm SBSD)	16.051	3
UR08	Alternative 1 (Resealing, provide with 25 mm SBSD)	24.541	1
UR09	Alternative 1 (Resealing, provide with 25 mm SBSD)	11.833	5
UR010	Alternative 1 (Resealing, provide with 25 mm SBSD)	6.207	12
UR011	Alternative 2 (Thin overlay of	6.993	11

	25 mm SDBC)		
UR012	Alternative 1 (Resealing, provide with 25 mm SBSD)	11.533	6
UR013	Alternative 1 (Resealing, provide with 25 mm SBSD)	21.63	2
UR014	Alternative 1 (Resealing, provide with 25 mm SBSD)	9.801	8
UR015	Alternative 1 (Resealing, provide with 25 mm SBSD)	11.126	7
UR016	Alternative 1 (Resealing, provide with 25 mm SBSD)	3.573	15

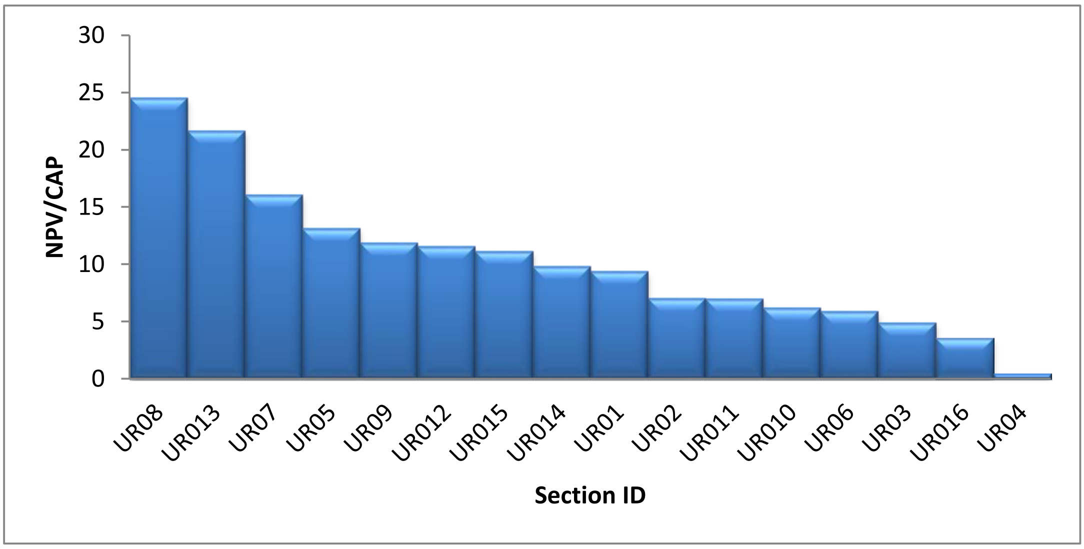


Fig. 4.29: Prioritization Ranking of Road Sections

4.6 COMPARATIVE STUDY OF SCHEDULED TYPE AND CONDITION RESPONSIVE TYPE M&R STRATEGY

The aim of present study is to compare the Scheduled type and Condition Responsive type Maintenance and Rehabilitation strategies. Effect of selecting a scheduled type M&R strategy with respect to a condition responsive type M&R strategy for UR01, UR02 and UR05 road sections has been calculated throughout the analysis period in this objective. The effect on the roughness progression for different sections due to scheduled or condition responsive maintenance has been studied. The economic indicators have been also summarized for various M&R alternatives. Three types of M&R alternatives have been considered for this objective and one as a base alternative for comparison *i.e.,* 'Routine Maintenance'. All these alternatives have been defined with two M&R strategies (intervention criteria's) *i.e.,* 'Scheduled' and 'Condition Responsive'. The details of these four alternatives with their intervention criteria's are given in Table 4.2.

4.6.1 Input Data

New Project named as 'Comparison between Scheduled and Condition Responsive M&R Strategy' was created which consisted of 'Patiala City Road Network' and 'Patiala City Vehicle Fleet'. Analysis period was taken as 15 years with start year of 2016. Project analysis has been chosen in the HDM-4 module with input and output currencies in Rupees.

4.6.2 Selection of Sections and Vehicles

For the present study objective, section id UR01, UR02 & UR05 have been selected from Patiala City road network. All the types of vehicle have been selected from Patiala City Vehicle Fleet for the analysis purpose. Fig. 4.30 shows the selection of sections for the project analysis.

4.6.3 Define Traffic

Normal traffic details such as Vehicular compositions with their annual average growth rate for both MT and NMT vehicles have been inputted for UR01, UR02 and UR05.

4.6.4 Proposed M&R Alternatives

The Scheduled M&R strategy has been chosen as per the current maintenance norms provided in MORT&H (2001b), whereas the Condition Responsive M&R strategy has been selected as per the serviceability levels up to which the respective pavement section is to be maintained

(Guidelines for Maintenance of Primary, Secondary and Urban Roads, MORT&H, 2004). Proposed M&R Alternatives have been presented in Table 4.12.

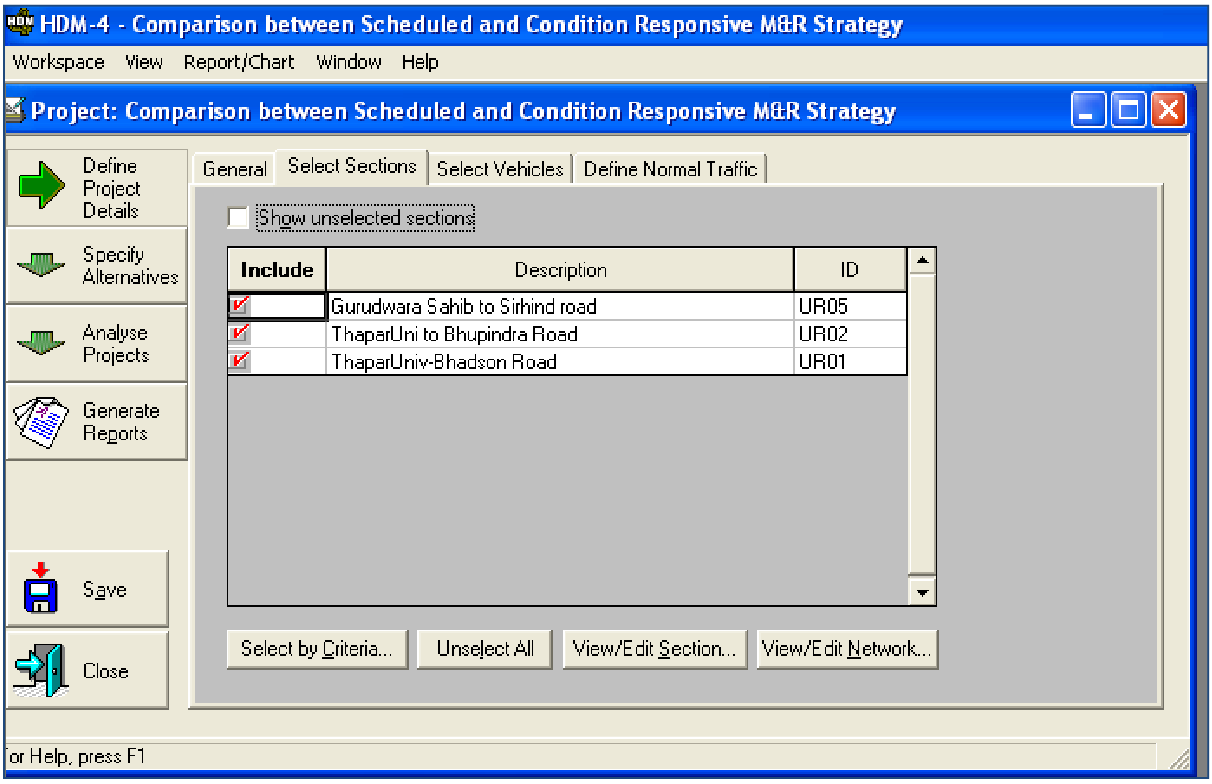


Fig. 4.30: Selection of UR01, UR02 & UR05 for Project Analysis

UR01, UR02 & UR05 comes under sub-arterial category of Indian urban roads. Serviceability levels for 'Other Roads' have been (kept in mind before) proposing the 'Condition Responsive' type M&R strategy for this project.

Table 4.12: Proposed M&R Alternatives for Project Analysis of UR01, UR02 and UR05

Works Standard	Description of Work	Scheduled Maintenance	Condition Responsive Maintenance
Routine Maintenance	Crack Sealing	Scheduled Annually	>10%
	Patching		>10%
	Pothole repair		>3 No.
	Ravel repair		>10%
	Drain cleaning		Scheduled annually
Resealing	Provide 25 mm SBSD	Scheduled every 4 years	Total damage area > 10% of total area

Thick Overlay	Provide 30 mm BC overlay	Scheduled Every 6 years	Roughness >4 m/km IRI
Strengthening & Rehabilitation	Provide (50 mm Dense Bituminous Macadam + 30 mm Bituminous Concrete)	Scheduled Every 9 years	Roughness > 6 m/km IRI and Carriageway cracked area > 15% of total area

4.6.5 Specify M&R Alternatives

Proposed M&R alternatives (presented in Table 4.12) have been specified in the project. Corresponding to these alternatives, M&R work items with their economic and financial unit costs have been assigned with the required intervention level. Fig. 4.31 shows the data input entry of M&R alternatives in project.

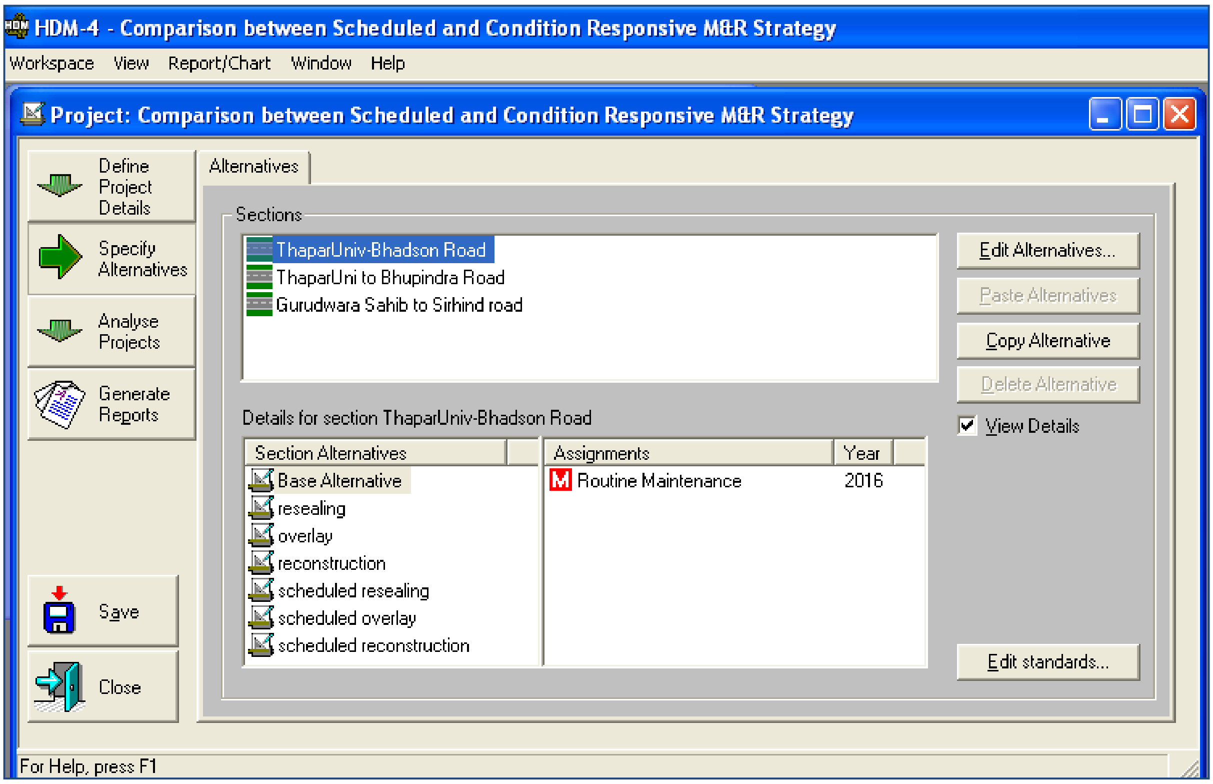


Fig. 4.31: Data Input Entry of M&R Alternatives in Project

4.6.6 Project Analysis

As the economic analysis for the selected section has to be done, so in Set-up Run of Project Analysis and 'Conduct Economic Analysis' has been selected. Base Alternative has been chosen for comparison purpose by default. Discount rate of 12 % was taken. The application was run for simulating the road condition of UR01, UR02 and UR05 under defined M&R alternatives throughout the analysis period of 15 years for this objective.

4.6.7 Roughness Progression

The Roughness progression graphs of three alternatives for UR05 have been shown in Figs. 4.32 - 4.34. The roughness progression has been traced to know whether the works have been correctly triggered corresponding to the specified intervention criteria. In case of 'Condition Responsive Overlay' alternative, Overlay work has been triggered as soon as the roughness value reaches 4 IRI. But in case of 'Scheduled Overlay' alternative, Overlay work has been triggered in every six years, but at roughness value of IRI of 3.2 m/km which is well below the limiting serviceability value of IRI of 4 m/km as shown in Fig. 4.32. In case of 'Condition Responsive strengthening & rehabilitation' alternative, maintenance work has been triggered as soon as the Roughness is greater than 6 m/km IRI and carriageway cracked area is greater than 15% of total area but in case of 'Scheduled strengthening & rehabilitation' alternative, maintenance work has been triggered in every nine years, but at roughness value of IRI of 3.0 m/km which is well below the limiting serviceability value of IRI of 6 m/km as shown in Fig. 4.33. In case of 'Condition Responsive Resealing' alternative, maintenance work has been triggered in year 2016, 2022 and 2027 but in case of 'Scheduled resealing' alternative, maintenance work has been triggered in every four years at 2016, 2020, 2024, 2028; but at damaged area which is well below the limiting serviceability value of 10 percent of total area. As per the analysis report, it has been concluded that under the scheduled maintenance strategy, maintenance activities are being carried out earlier as compared to responsive maintenance strategies which leads to the higher road agency cost.

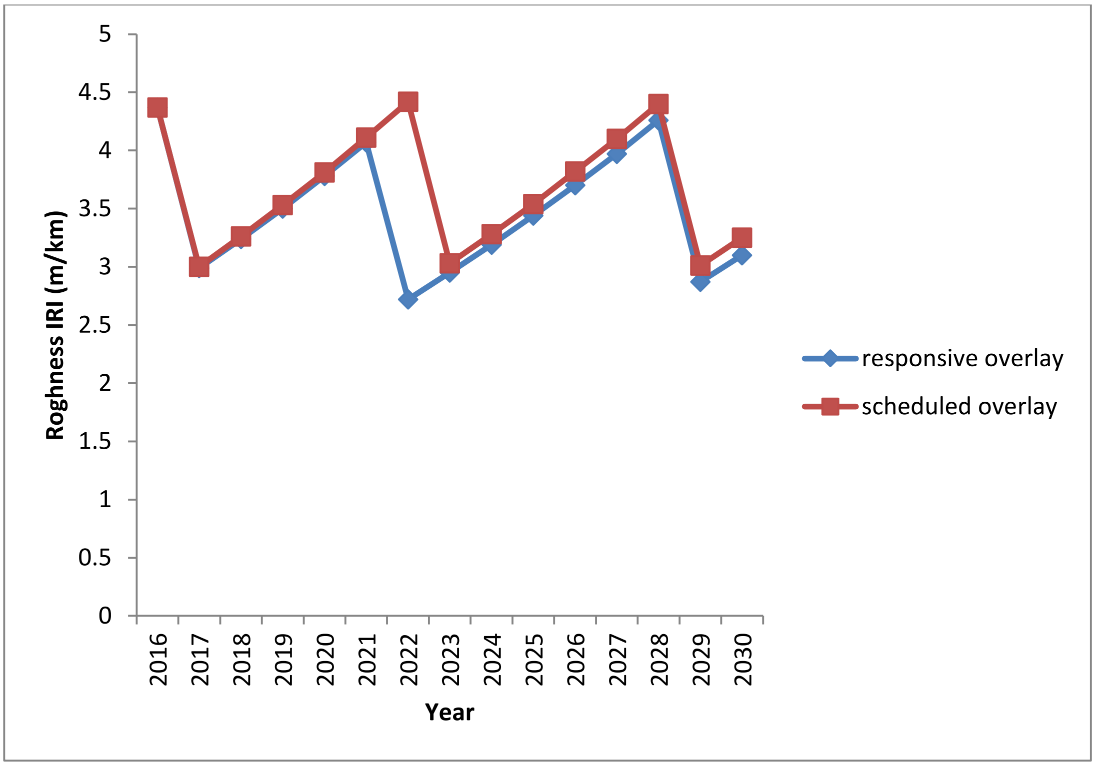


Fig. 4.32: Roughness Progression under the 'Condition & Responsive' Alternative of overlay for UR05

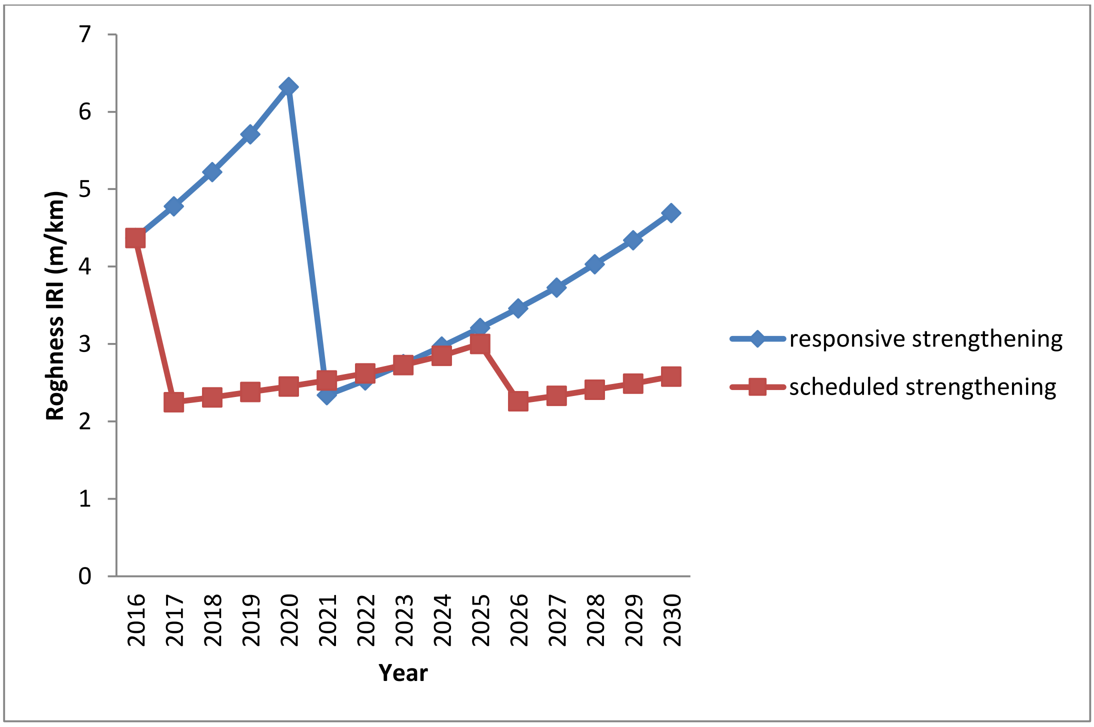


Fig. 4.33: Roughness Progression under the 'Condition & Responsive' Alternative of Strengthening & Rehabilitation for UR05

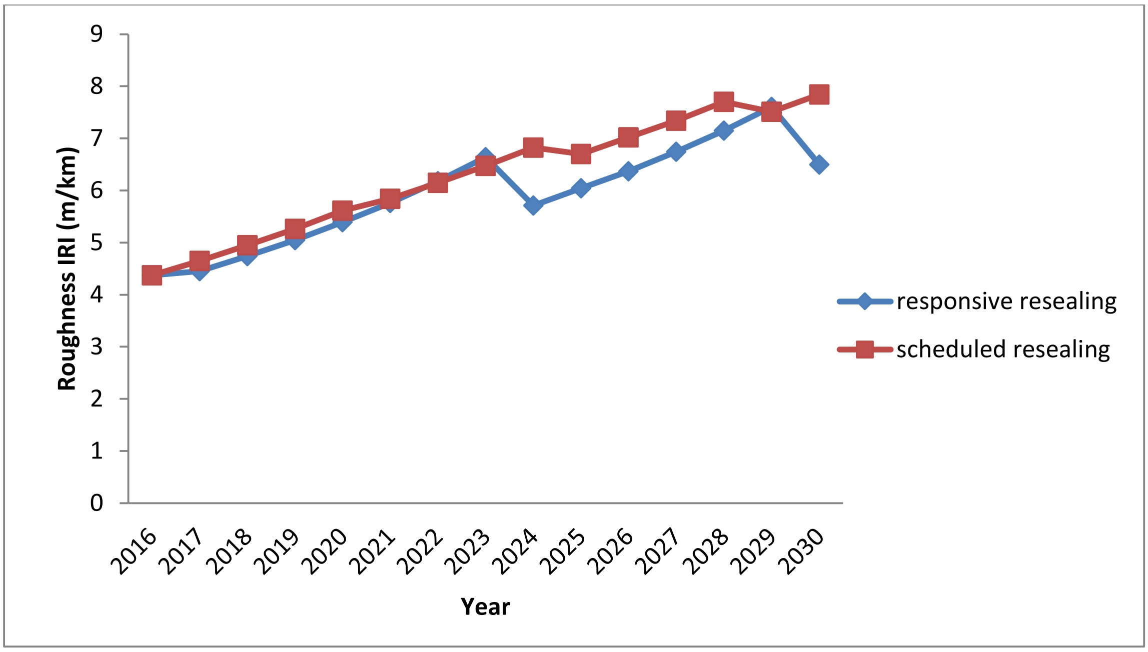


Fig. 4.34: Roughness Progression under the 'Condition & Responsive' Alternative of Resealing for UR05

4.6.8 Economic Analysis of Scheduled and Responsive Maintenance Strategies

The economic analysis summary for section UR01, UR02 & UR05 has been given in Table 4.13 which gives a comparison of the NPV/CAP ratio (Net Present Value / Capital Cost) for the three alternatives with respect to the base alternative. In terms of the economic indicator NPV/CAP, the condition responsive maintenance strategy gives a higher value of NPV/CAP as compared to scheduled maintenance strategy. Hence, maintenance decisions with condition responsive have been selected as an optimum M&R alternative.

Table 4.13: Economic Analysis Results for Scheduled & Condition Responsive M&R Strategy

Section Detail	NPV/CAP ratio		
	Alternative	**Scheduled Maintenance**	**Condition Responsive Maintenance**
UR01	Resealing	3.907	6.289
	Overlay	4.119	4.938
	Strengthening & Rehabilitation	2.567	5.770
UR02	Resealing	6.935	9.750

	Overlay	5.150	5.295
	Strengthening & Rehabilitation	3.479	6.196
UR05	Resealing	3.784	7.171
	Overlay	5.158	5.458
	Strengthening & Rehabilitation	3.267	5.909

4.7 LIFE CYCLE COST ANALYSIS FOR URBAN ROAD NETWORK OF PATIALA

Program Analysis application module of HDM-4 has been run to compare the total life-cycle cost for the analysis period of 10 years, including the RAC and RUC for all the ninety six defined section alternatives under scheduled and condition responsive treatments.

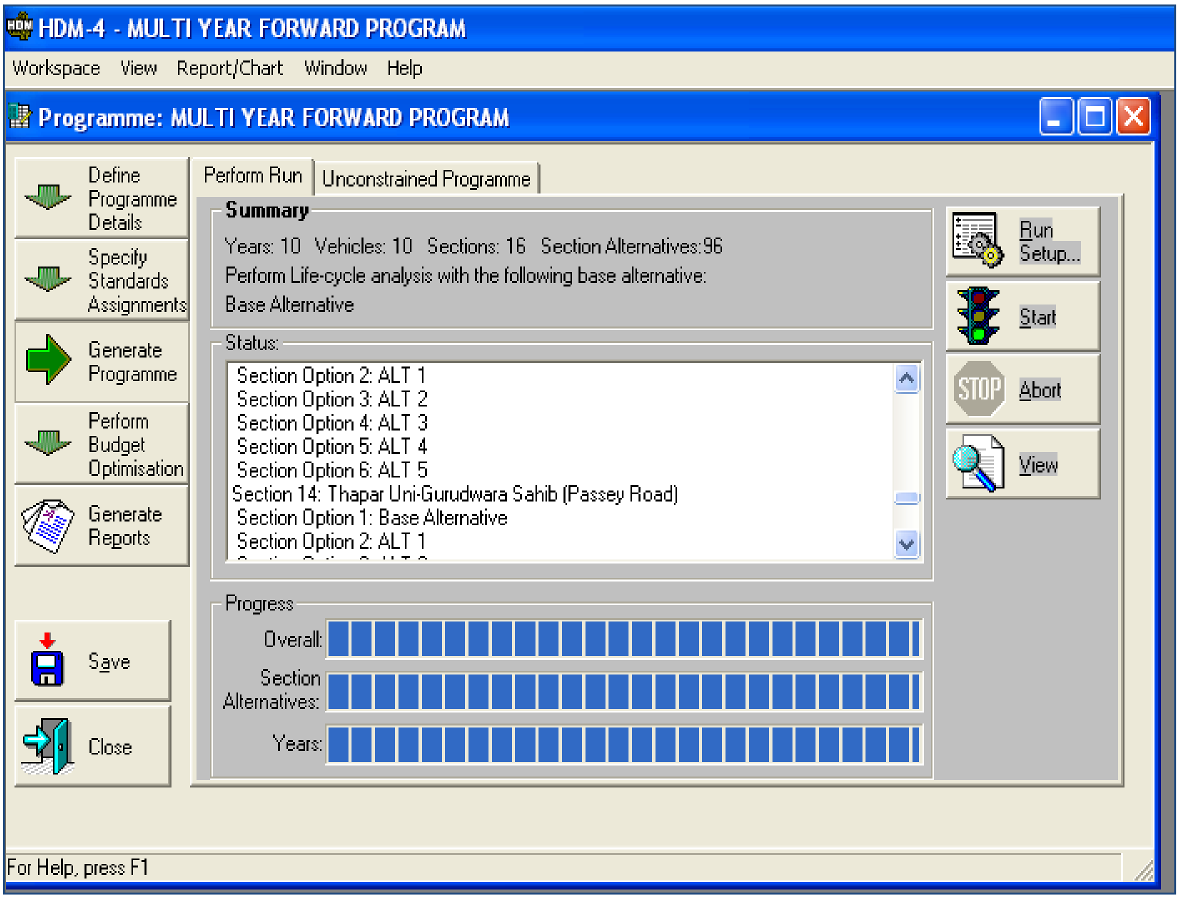


Fig. 4.35: Life-Cycle Cost Analysis for Patiala Urban Road Network

The program application has been run for life cycle cost analysis of the Patiala city network comprising of 16 pavement sections and represented in Fig. 4.35.

4.7.1 Budget Requirements

The budget requirements in the analysis period for the Patiala City road network under the 'Maintenance Alternatives' are shown in Fig. 4.36 and the section wise budget requirements for the Patiala City road network under the 'Maintenance Alternatives' as given in Table 4.14. It is quite clear from this figure that around 49% of the total fund requirements will be required in the year 2016 and 2017 of the analysis period as eleven pavement sections of the selected road network needs urgent maintenance works to be carried out in these years. For rest of the years after 2017, the fund requirement for the maintenance works decreases as per the analysis report**.** Also it has been observed that the average IRI of the urban road network reduces from 4.7 m/km to 3.15 m/km if the network has been maintained with unconstrained budget scenario.

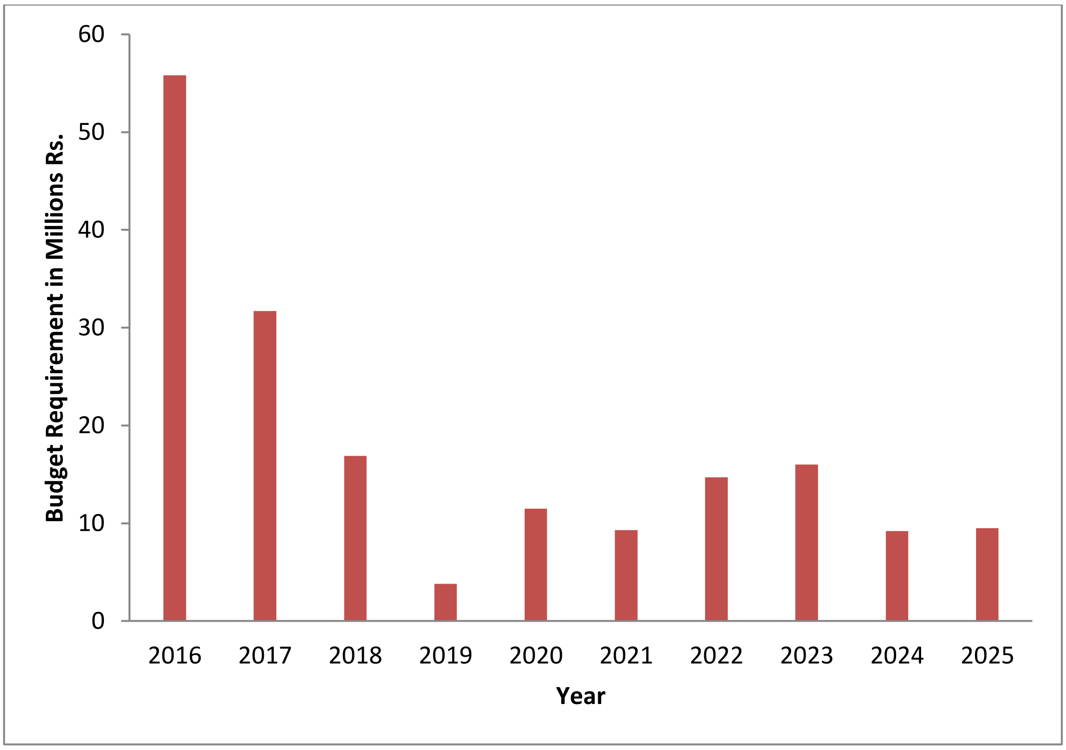


Fig. 4.36: Year-wise Budget Requirements for the Patiala City Network

Table 4.14: Summary of Life Cycle Cost Analysis (Unconstrained Works Programme)

Section ID	Name of Road	Work Description	Year	Financial Cost	Cumulative Cost	NPV/CAP
UR02	Thapar University -	Thin Overlay > 4 IRI	2016	3.3600	3.4	1.774

	Bhupindra Road					
UR010	Bus Stand Chowk - Gurbax Colony	Thin Overlay > 4 IRI	2016	4.3680	7.7	2.303
UR011	Fountain Chowk - Leela Bhawan	Thin Overlay > 4 IRI	2016	2.8000	10.5	1.819
UR012	Fountain Chowk - Lowemall	Thin Overlay > 4 IRI	2016	7.3440	17.9	2.803
UR07	Gurudwara Shahib - Bus Stand Road	Thin Overlay > 4 IRI	2016	1.9325	19.8	2.315
UR05	Gurudwara Shahib - Sirhind road	Thin Overlay > 4 IRI	2016	10.3066	30.1	4.253
UR014	Leela Bhawan Chowk - 22 no Bridge	Thin Overlay > 4 IRI	2016	4.7040	34.8	3.2
UR016	Leela Bhawan Chowk - Baradari Garden	Thin Overlay > 4 IRI	2016	2.2880	37.1	1.995
UR013	Thapar University - Gurudwara Shahib (Sect. Road)	Reconstruction >6IRI & CA>15	2016	16.6550	53.8	5.646
UR03	Thapar University - Gurudwara Shahib (Passey Road)	Thin Overlay > 4 IRI	2016	2.0800	55.8	2.588
UR010	Busstand Chowk - Gurbax Colony	Thin Overlay > 4 IRI	2017	4.3680	60.2	2.303
UR07	Gurudwara Shahib - Busstand Road	Thin Overlay > 4 IRI	2017	1.9325	62.1	2.315
UR06	Leela Bhawan	Thin Overlay > 4 IRI	2017	2.3520	64.5	1.624

	Chowk - Cantonment					
UR015	Leela bhawan Chowk - Gurudwara Shahib	Thin Overlay > 4 IRI	2017	5.8400	70.3	3.173
UR09	Thikriwala ji Chowk - Badungar Road	Thin Overlay > 4 IRI	2017	2.1760	72.5	3.818
UR08	Thikriwala ji Chowk - Sangrur Road	Reconstruction >6IRI & CA>15	2017	14.9687	87.5	6.597
UR011	Fountain Chowk - Leela Bhawan	Thin Overlay > 4 IRI	2018	2.8000	90.3	1.819
UR012	Fountain Chowk - Lowermall	Thin Overlay > 4 IRI	2018	7.3440	97.6	2.803
UR014	Leela Bhawan Chowk - 22 no Bridge	Thin Overlay > 4 IRI	2018	4.7040	102.3	3.2
UR03	Thapar University - Gurudwara Shahib (Passey Road)	Thin Overlay > 4 IRI	2018	2.0800	104.4	2.588
UR01	Thapar University - Bhadson Road	Thin Overlay > 4 IRI	2019	1.7178	106.1	1.97
UR09	Thikriwala ji Chowk - Badungar Road	Thin Overlay > 4 IRI	2019	2.1760	108.3	3.818
UR02	Thapar University - Bhupindra Road	Thin Overlay > 4 IRI	2020	3.3600	11.7	1.774
UR015	Leela Bhawan Chowk - Gurudwara Shahib	Thin Overlay > 4 IRI	2020	5.8400	117.5	3.173
UR016	Leela	Thin Overlay	2020	2.2880	119.8	1.995

	Bhawan Chowk - Baradari Garden	> 4 IRI				
UR011	Fountain Chowk - Lower Mall	Thin Overlay > 4 IRI	2021	7.3440	127.1	2.803
UR07	Gurudwara Shahib - Bus Stand Road	Thin Overlay > 4 IRI	2021	1.9325	129.1	2.315
UR05	Gurudwara Shahib - Sirhind Road	Thin Overlay > 4 IRI	2022	10.3066	139.4	4.253
UR04	Passey Road - Civil Line (Ghuman Road)	Thin Overlay > 4 IRI	2022	2.3040	141.7	0.061
UR09	Thikriwala ji Chowk - Badungar Road	Thin Overlay > 4 IRI	2022	2.1760	143.8	3.818
UR02	Thapar University - Bhupindra Road	Thin Overlay > 4 IRI	2023	3.3600	147.2	1.774
UR010	Bus Stand Chowk - Gurbax Colony	Thin Overlay > 4 IRI	2023	4.3680	151.6	2.303
UR06	Leela Bhawan Chowk - Cantonment	Thin Overlay > 4 IRI	2023	2.3520	153.9	1.624
UR015	Leela Bhawan Chowk - Gurudwara Shahib	Thin Overlay > 4 IRI	2023	5.8400	159.8	3.173
UR01	Thapar University - Bhadson Road	Thin Overlay > 4 IRI	2024	1.7178	161.5	1.970
UR011	Fountain Chowk - Leela Bhawan	Thin Overlay > 4 IRI	2024	2.8000	164.3	1.819

UR014	Leela Bhawan Chowk - 22 no Bridge	Thin Overlay > 4 IRI	2024	4.7040	169	3.2
UR011	Fountain Chowk - Lower Mall	Thin Overlay > 4 IRI	2025	7.3440	176.3	2.803
UR09	Thikriwala ji Chowk - Badungar Road	Thin Overlay > 4 IRI	2025	2.1760	178.5	3.818

***** All costs are expressed in million Indian Rupees

4.7.2 Budget Optimisation

If the estimate of the required road agency cost for the maintenance works is lesser than sanctioned budgets for the maintenance activities for a particular year in the Patiala city, the unconstrained works programme will be implemented as such without any problem or changes. But if the estimate of the maintenance works as suggested by HDM under unconstrained condition is higher than the sanctioned budget, then the budget optimisation technique has to be adopted under multiyear forward programme of HDM-4.

After performing the budget optimisation, a revised work programme is obtained from HDM-4 analysis which will have total maintenance cost required within the sanction budget to the authorities.

4.7.3 Optimized Works Programme

The budget optimisation process using 'Incremental Analysis Method' has been performed with Rs. 90 million budget availability, as against the requirement of Rs. 178.5 million for the analysis period of 10 years as shown in Fig. 4.37.

This process results in an optimized works programme list as presented in Table 4.15. This optimized works programme has total budget requirements of Rs. 89.10 million, which is around the available budget of Rs. 90 million. Average IRI value of project remains around IRI of 4.93 m/km due to limited funds available for taking the maintenance activities.

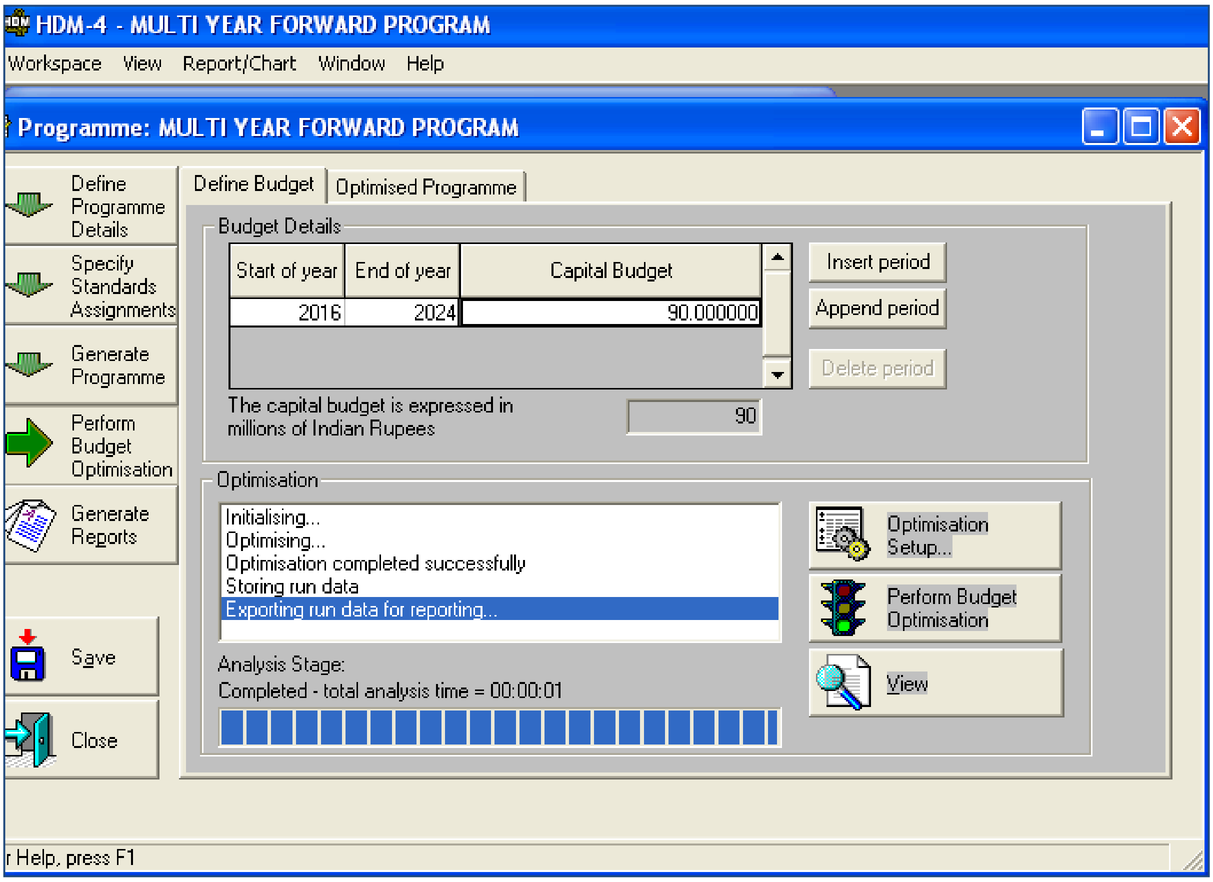


Fig. 4.37: Budget Optimisation Process for Program Analysis

Table 4.15: Section-wise Optimized Works Programme List with Constrained Budget of Rs. 90 million

Section ID	Name of Road	Work Description	Year	Financial Cost	Cumulative Cost	NPV/CAP
UR02	Thapar University - Bhupindra Road	Reseal at 10%	2016	2.1000	2.1	1.747
UR010	Bus Stand Chowk - Gurbax Colony	Reseal at 10%	2016	2.7300	4.8	3.191
UR011	Fountain Chowk - Leela Bhawan	Reseal at 10%	2016	1.7500	6.6	2.313
UR012	Fountain Chowk - Lowe Mall	Reseal at 10%	2016	4.5900	11.2	3..901
UR07	Gurudwara Shahib - Bus Stand	Reseal at 10%	2016	1.2078	12.4	3.684

	Road					
UR05	Gurudwara Shahib - Sirhind Road	Thin Overlay > 4 IRI	2016	10.3066	22.7	4.253
UR014	Leela Bhawan Chowk - 22 no Bridge	Reseal at 10%	2016	2.9400	25.6	3.774
UR015	Leela Bhawan Chowk - Gurudwara Shahib	Reseal at 10%	2016	3.6500	29.3	3.183
UR016	Leela Bhawan Chowk - Baradari Garden	Thin Overlay > 4 IRI	2016	2.2880	31.6	1.995
UR013	Thapar University - Gurudwara Shahib (Sect. Road)	Reseal at 10%	2016	3.2850	34.8	9.899
UR03	Thapar University - Gurudwara Shahib (Passey Road)	Reseal at 10%	2016	1.3000	36.1	2.395
UR09	Thikriwala ji Chowk - Badungar Road	Reseal at 10%	2016	1.3600	37.5	5.308
UR08	Thikriwala ji Chowk - Sangrur Road	Reseal at 10%	2016	2.9524	40.5	12.604
UR06	Leela Bhawan Chowk - Cantonment	Thin Overlay > 4 IRI	2017	2.3520	42.8	1.624
UR01	Thapar University - Bhadson Road	Thin Overlay > 4 IRI	2019	1.7178	44.5	1.970
UR016	Leela Bhawan Chowk - Baradari	Thin Overlay > 4 IRI	2020	2.2880	46.8	1.995

	Garden					
UR05	Gurudwara Shahib - Sirhind Road	Thin Overlay > 4 IRI	2022	10.3066	57.1	4.253
UR015	Leela Bhawan Chowk - Gurudwara Shahib	Reseal at 10%	2022	3.6500	60.8	3.183
UR08	Thikriwala ji Chowk - Sangrur Road	Reseal at 10%	2022	2.9524	63.7	12.604
UR02	Thapar University - Bhupindra Road	Reseal at 10%	2023	2.1000	65.8	1.747
UR010	Bus Stand Chowk - Gurbax Colony	Reseal at 10%	2023	2.7300	68.6	3.191
UR011	Fountain Chowk - Lower Mall	Reseal at 10%	2023	4.5900	73.1	3.901
UR07	Gurudwara Shahib - Bus Stand Road	Reseal at 10%	2023	1.2078	74.4	3.684
UR06	Leela Bhawan Chowk - Cantonment	Thin Overlay > 4 IRI	2023	2.3520	76.7	1.624
UR013	Thapar University - Gurudwara Shahib (Sect. Road)	Reseal at 10%	2023	3.2850	80.0	9.899
UR09	Thikriwala ji Chowk - Badungar Road	Reseal at 10%	2023	1.3600	81.4	5.308
UR01	Thapar University - Bhadson Road	Thin Overlay > 4 IRI	2024	1.7178	83.1	1.970
UR011	Fountain Chowk - Leela Bhawan	Reseal at 10%	2024	1.7500	84.8	2.313

UR014	Leela Bhawan Chowk - 22 no Bridge	Reseal at 10%	2024	2.9400	87.8	3.774
UR03	Thapar University - Gurudwara Shahib (Passey road)	Reseal at 10%	2025	1.3000	89.1361	2.395

*****All costs are expressed in: Indian Rupees (millions)

4.7.4 Determination of Effect of Budget Reduction on Road Condition

This study shows the effect of reduction in budget allocations on the condition and serviceability level of urban road pavement network of Patiala city. The pavement condition of the roughness progression has been compared by taking different amounts of budget allocations. Pavement maintenance treatment strategies, as taken earlier for life cycle cost analysis, have been used to run this programme. The budget optimization process has been carried out with three different budget allocations of 50, 100, 150, 178.5 million (Indian rupees). The effect of different budget allocation levels on the condition of the pavement surface is measured in terms of roughness progression as shown in Fig. 4.38. The average roughness value of IRI 7.67 m/km in year 2025 in case of the low budget allocation of 50 million Indian rupees is very high as compared to average IRI of 4.00 m/km in the same year with budget allocation of 150 million Indian rupees. These types of low budget allocations will definitely result in the increase in the road user cost.

4.7.5 Determination of Effect of Deferred Maintenance on Patiala Urban Road Network Condition

The condition of the pavement surface will deteriorate because of the postponement of the required maintenance & rehabilitation strategies. The difference in the condition of the pavement surface, measured in terms of average roughness progression in IRI, shows the effect of delayed maintenance and hence the increase in the road user cost because of the delayed maintenance. The input data for this case study included all 16 Patiala road sections. Four alternatives of M&R strategies namely;

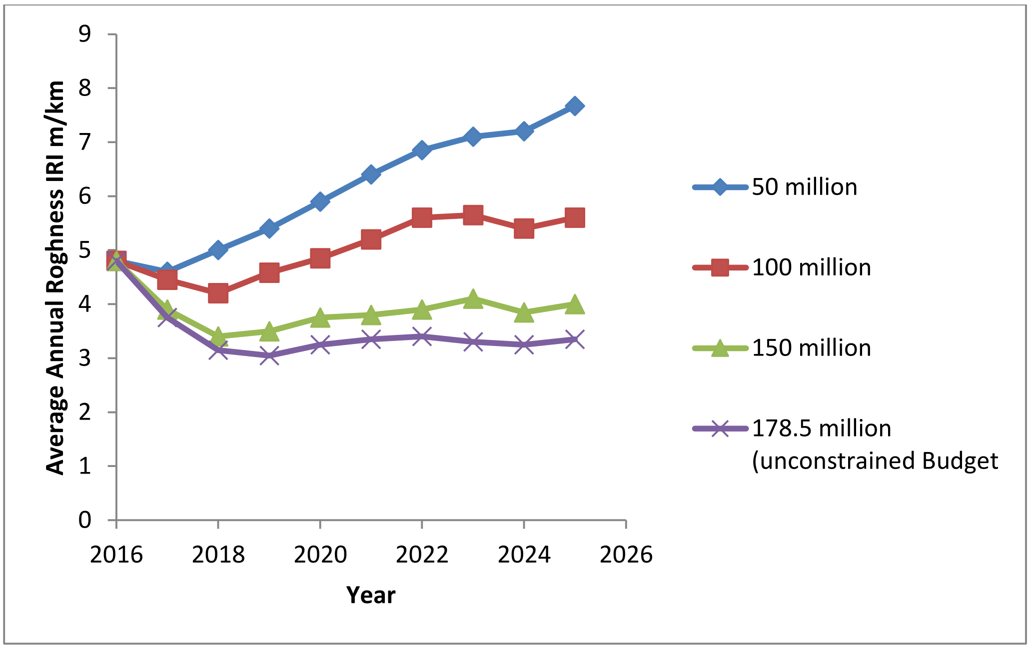


Fig. 4.38: Average Roughness Value for Different Budget Levels

M&R-2016, M&R-2017, M&R-2018 and M&R-2019 have been assigned for all the 16 road sections of Patiala city. Maintenance works and the intervention criteria are defined as per the codal provisions so as to keep the pavement conditions within the required levels of serviceability, but the starting year is different for all the 4 cases with a delay of one year in each strategy. The selection of M&R strategies in HDM-4 is shown in Fig. 4.39.

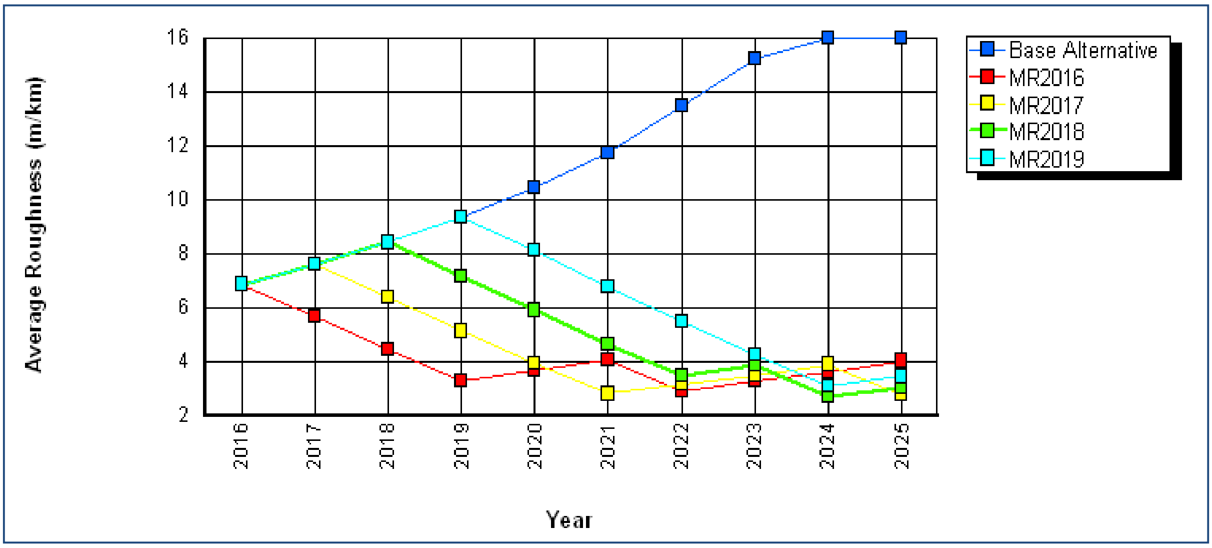


Fig. 4.39: Average Roughness Value for Delayed Maintenances (MR2016, MR2017, MR2018 & MR2019) for UR013

It has been observed from the Fig. 4.39 that the average roughness value of the urban road network will change significantly if the maintenance is delayed.

The value of roughness reaches 9.2 m/km in the year 2019 if the maintenance is delayed by 4 years but if the maintenance is triggered as per the respective intervention level, the value of IRI is around 3.65 m/km in the year 2019. This will result in very high vehicle operation cost for the road users.

4.7.6 Conclusion

- All the road sections taken in this study of Patiala city will be needing reconstruction work within 0 to 9 years if no maintenance and rehabilitation work is assigned to the road sections throughout the intervening period.
- On the basis of the economic analysis summary, the optimum M&R strategy selected for sections UR03, UR07, UR08, UR09, UR010, UR012, UR013, UR014, UR015, UR016 is Alternative 1 (Resealing 25 mm SBSD) and for all other sections Alternative 2 (Thin overlay 25 mm SDBC) has been the optimum maintenance strategy with maximum NPV/CAP value.
- An economic indicator proves that the condition responsive maintenance strategy gives a higher value of NPV/CAP ratio as compared to the scheduled maintenance strategy. Hence, maintenance decisions with condition responsive have been selected as an optimum M&R alternative.
- Reducing the annual budget funds for the maintenance of pavement network of urban roads will have significant negative impact on the pavement condition which will increase the road user cost and faster deterioration of pavement surface.
- Delaying the maintenance activities has a negative impact on the overall condition of the pavement surface. The value of IRI touched 9.2 m/km in the year 2019 if the maintenance work is delayed by 4 years but if the maintenance is triggered as per the respective intervention level, the value of IRI is around 3.65 m/km in the year 2019.

CHAPTER 5

GENETIC PROGRAMMING AND NEURAL NETWORK MODELS FOR PREDICTION OF PAVEMENT DISTRESS

5.1 GENERAL

This chapter includes the development Genetic Programming (GP) models and neural network models for the prediction of pavement distress. The dataset used for development of GP models and neural network models are same as used for HDM models for the prediction of pavement distress (details are presented in Chapter 3). In this chapter, we have also taken an attempt to display developed PMMS graphically using Geographical Information System (GIS).

5.2 INTRODUCTION TO GENETIC PROGRAMMING

GP has commenced as an endeavor to discover how computers could be trained to solve problems without being explicitly programmed to do so. GP is an extension to genetic algorithms proposed by Koza (1992) who defines GP as a domain independent problem solving approach in which computer programs are evolved to solve, or approximately solve, problems based on Darwinian principle of reproduction and analogs of naturally occurring genetic operations such as reproduction, crossover and mutation. The five major prelude steps for the basic version of GP require the user to specify: a) the set of terminals for each stem of the to-be-evolved program; b) the set of primitive functions for each stem of the to-be-evolved program; c) the fitness measure; d) certain parameters for controlling the run; e) the termination criterion and method for designating the result of the run.

5.2.1 Steps to execute Genetic Programming

GP has been initiated with a population of randomly generated computer programs composed of the available programmatic ingredients. It iteratively transforms a population of computer programs into a new generation of the population by applying analogs of naturally occurring genetic operations. These operations are applied to individual(s) selected from the population. The individuals have been elected to participate in the genetic operations based on their fitness. The iterative transformation of the population is implemented inside the main generational loop of the run of genetic programming. The execution steps of GP (that is, the flowchart of genetic programming in Fig. 5.1) are as follows:

1. Randomly create an initial population (generation 0) of individual computer programs composed of the available functions and terminals.
2. Iteratively perform the following sub-steps (called a generation) on the population until the termination criterion is satisfied:
    a) Execute each program in the population and ascertain its fitness (explicitly or implicitly) using the problem's fitness measure.
    b) Select one or two individual program(s) from the population with a probability based on fitness (with reselection allowed) to participate in the genetic operations in (c).
    c) Create new individual program(s) for the population by applying the following genetic operations with specified probabilities:
    d) Reproduction: Copy the selected individual program to the new population.
    e) Crossover: Create new offspring program(s) for the new population by recombining randomly chosen parts from two selected programs.
    f) Mutation: Create one new offspring program for the new population by randomly mutating a randomly chosen part of one selected program.
    g) Architecture-altering operations: Choose an architecture-altering operation from the available repertoire of such operations and create one new offspring program for the new population by applying the chosen architecture-altering operation to one selected program.

3. After the termination criterion is satisfied, the single best program in the population produced during the run (the best-so-far individual) is harvested and designated as the result of the run. If the run is successful, the result may be a solution (or approximate solution) to the problem.

5.3 GP Kernel Program

The GP kernel program uses genetic programming (Koza, 1992) for finding functions based on data. The program is a command line tool, in the sense that it has to be invoked from the command prompt with additional parameters. These parameters are the name of the file containing detailed information on the problem and the direction of the flux of information between the global parameter file and the subdirectory located parameter files. After having set up the configuration files the program can be run, resulting some output files.

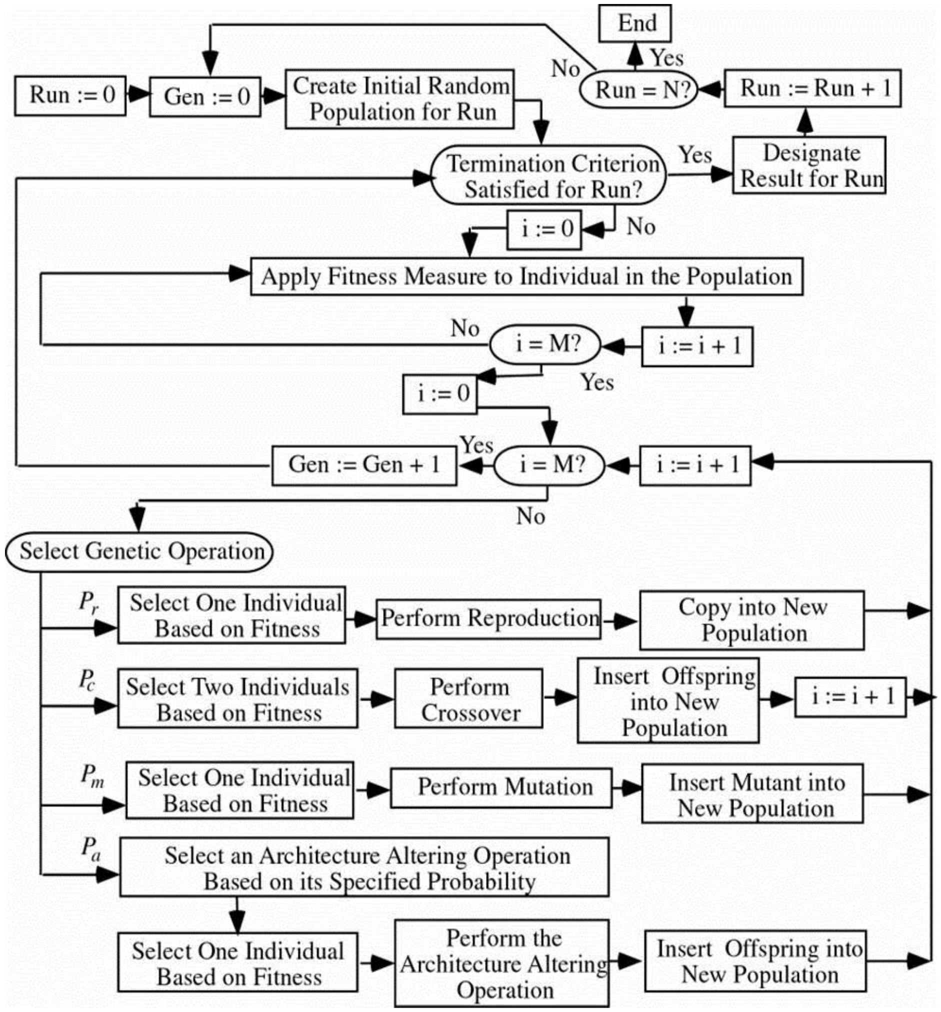


Fig. 5.1: Genetic Programming Flow Chart (Koza, 1992)

5.3.1 Summary of GP Kernel Steps

[1] Create the data file and save in the same directory as the genetic program

(*e.g. C:\project\project1.csv*)

[2] We have to run

gpkernel *project1**.ini ini2dir***

to create the specific directory for GP kernel. This will create the general ini file (*e.g. project1.ini*), as well as the directory and sub-directory containing the necessary files.

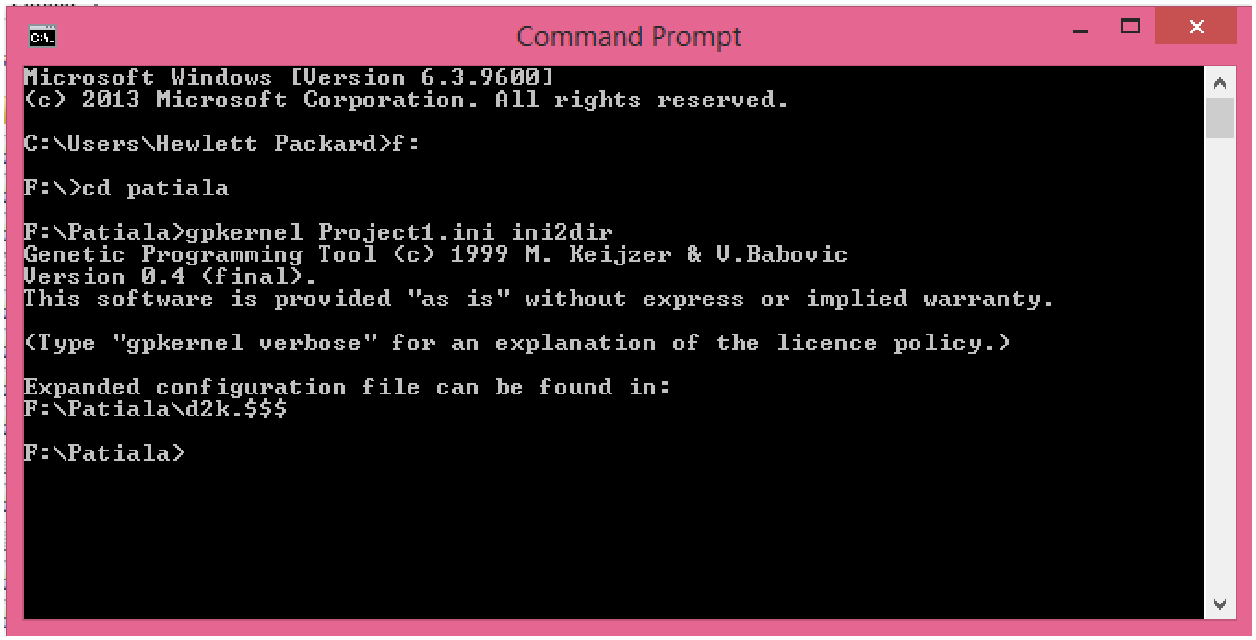


Fig. 5.2: Creation of a Directory Structure

[3] In the dataSource subdirectory we change **sourcefile**

i.e., at the file *C:\project\d2k.$$$\project1.d2k**dataSource****data.ini,***

we change **sourcefile**=project1.csv

[4] Run

gpkernel** project1**.ini fromdir

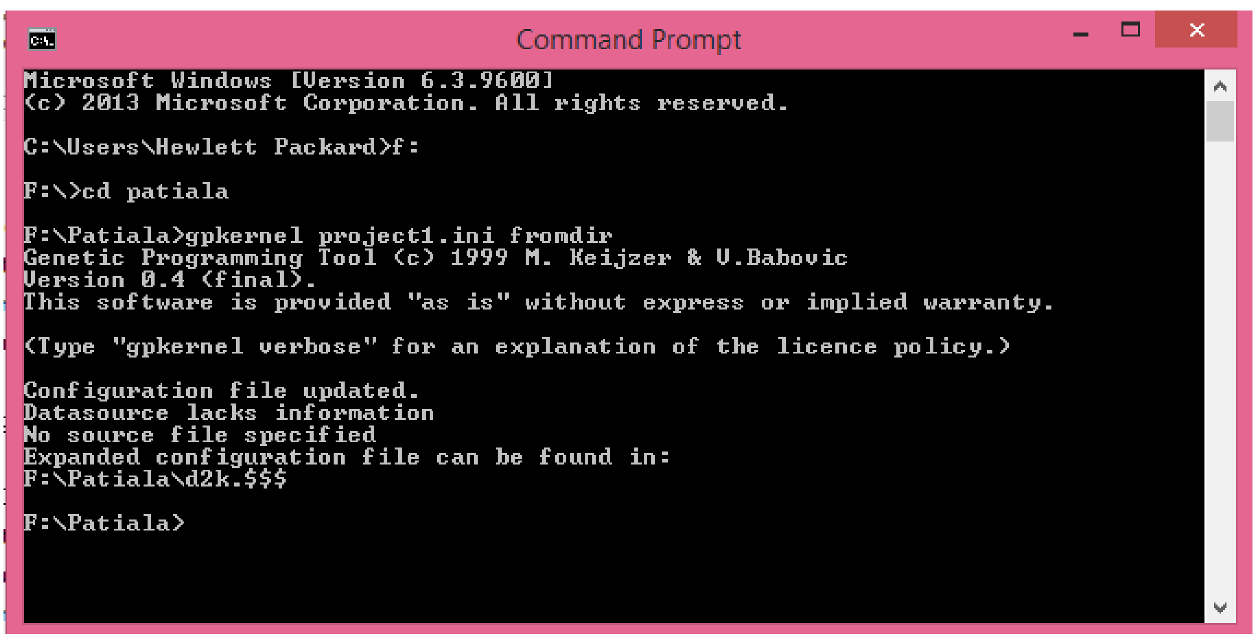


Fig. 5.3: Running a Command to Reflect Changes to the Subdirectories

the parameter ***fromdir*** is used because we have done changes within the structure directory that we want to be reflect both on the ini file and on the rest of the subdirectory structure.

[5] In the dataSource subdirectory change (in the ***data.ini*** file again) other parameters such as the existence of headers, delimiter, size of the training set, *etc*.

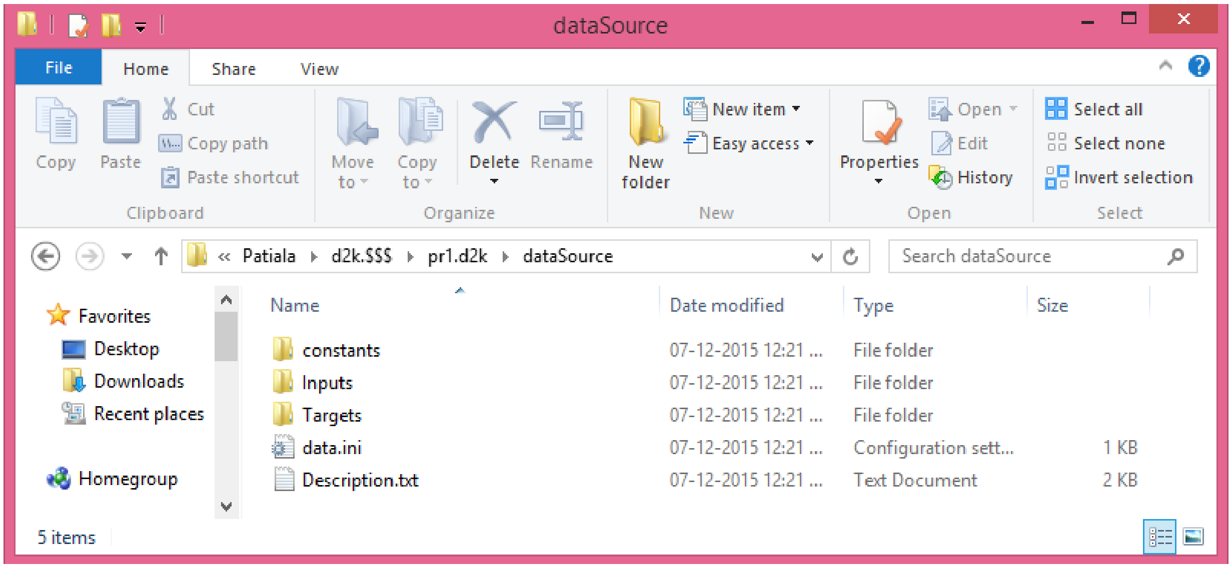


Fig. 5.4: Data Source: A directory Created by GP Kernel

[6] Run

gpkernel *project1****.ini fromdir***

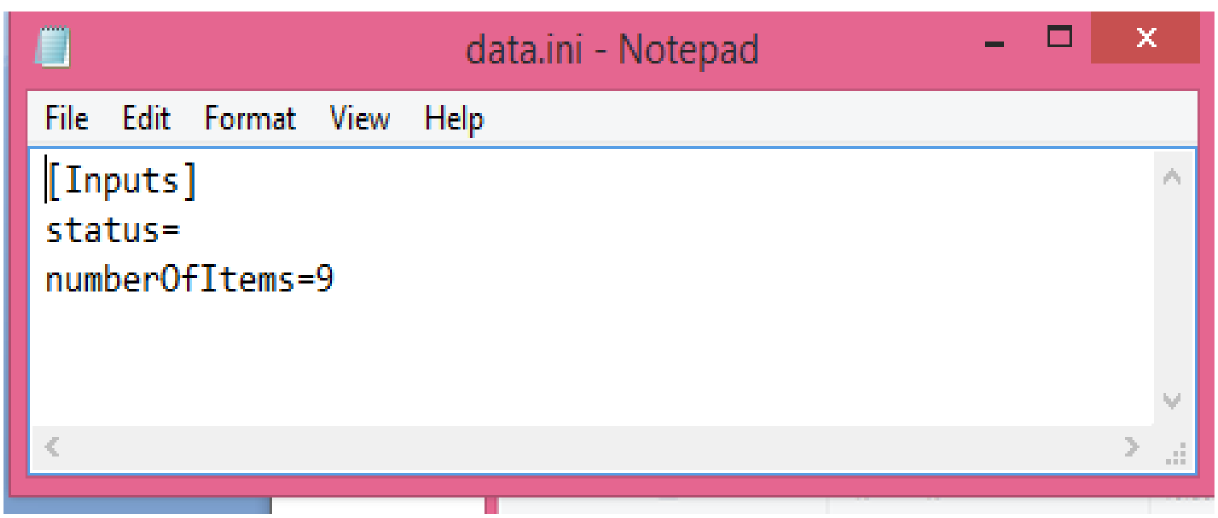


Fig. 5.5: File indicating the Number of Inputs for an Experiment

[7] To add dimension information, change in the file

C:\project\d2k.$$$\project1.d2k**Dimension\data.ini** the item **NumberOfItems=_** to the number of magnitudes dimensions.

[8] Run

gpkernel *project1****.ini fromdir***

This will create subdirectory for all the dimensions, in each subdirectory

…**Dimension\Dimension**x

change the **data.ini** file:

dimensionName=Length

dimAbbreviated=L

unitName=meter

unitAbbreviated=m

[9] Run

gpkernel *project1****.ini fromdir***

This will affect the information contained for the different **Inputs**, **Targets**, and **Constants** information, that will be created next.

[10] Change in the **…*dataSource\inputs\data.ini*** file

NumberOfItems=__

gpkernel *project1****.ini fromdir***

Then we will have to create the subdirectory for the different input sets.

[11] For each Inputs_, change the name, location in the source file (0, 1, …), and dimensions (if necessary).

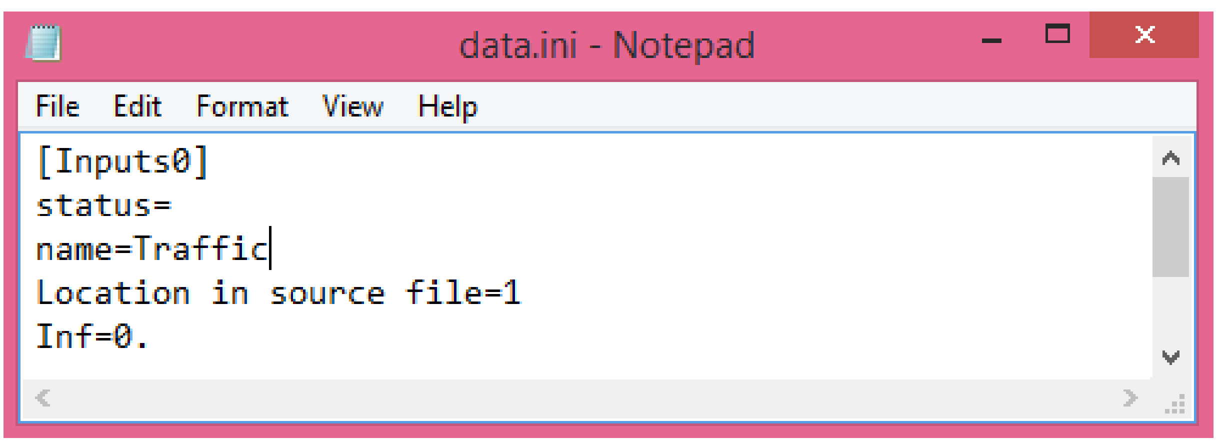


Fig. 5.6: Setting an Input Parameter

[12] Do the same for the target field (Step 10. and Step11.)

[13] Proceed analogously with the constants

[14] The general **ini** file should show in the section **[dataSource]** the line

status=done

Now, the data source is properly setup.

[15] Change in the pool subdirectory the value of

NumberOfItems=*1* (*e.g.*)

gpkernel *project1****.ini fromdir***

Then the following message appears:

Pool0 is not ready yet. Check parameters and status.

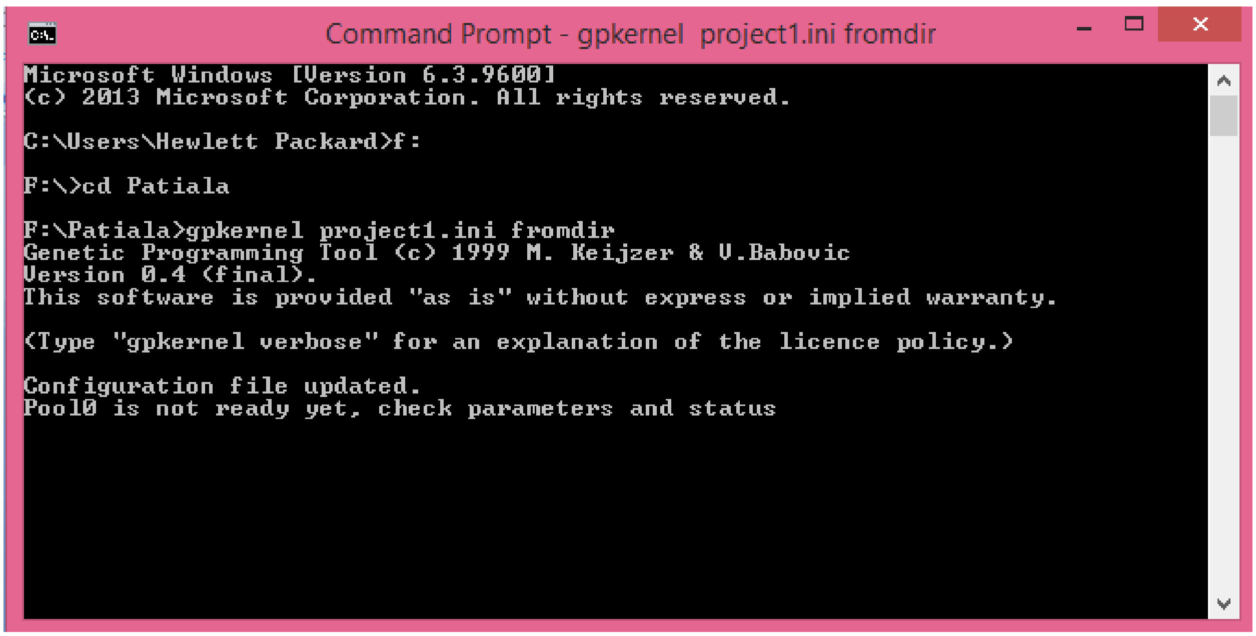


Fig. 5.7: Message from the GP Kernel to set the POOL Parameters

[16] Now do pool settings,

a) Objective: number, ***gpkernel*** *project1****.ini fromdir***

For each objective we can set:

objectivetype= CoD / RMS / UnitError / FitnessPerNode /…

b) Change the settings of ini file in …\lTable

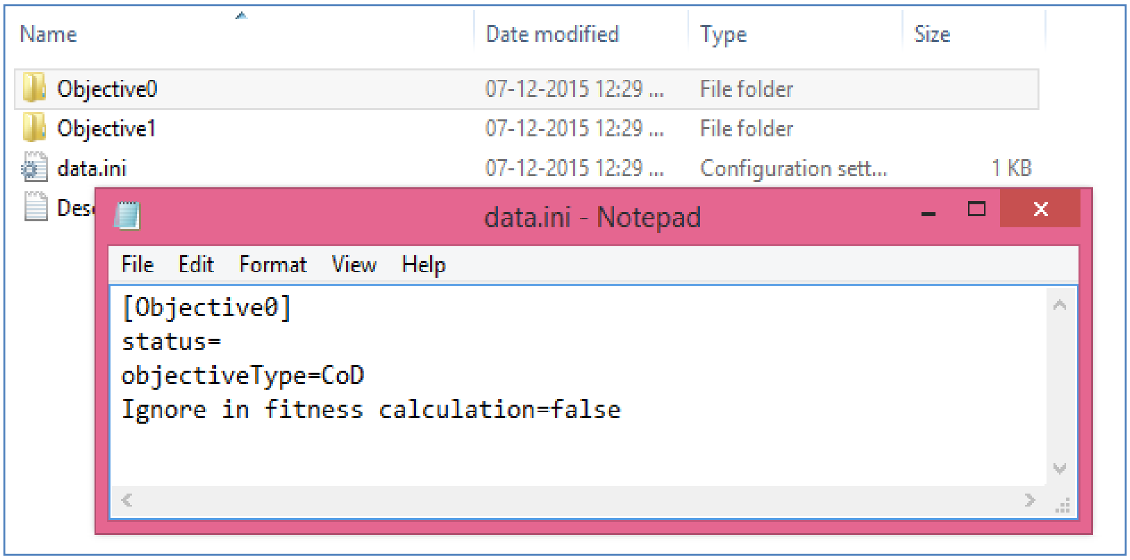


Fig. 5.8: Setting Parameters of Fitness Functions

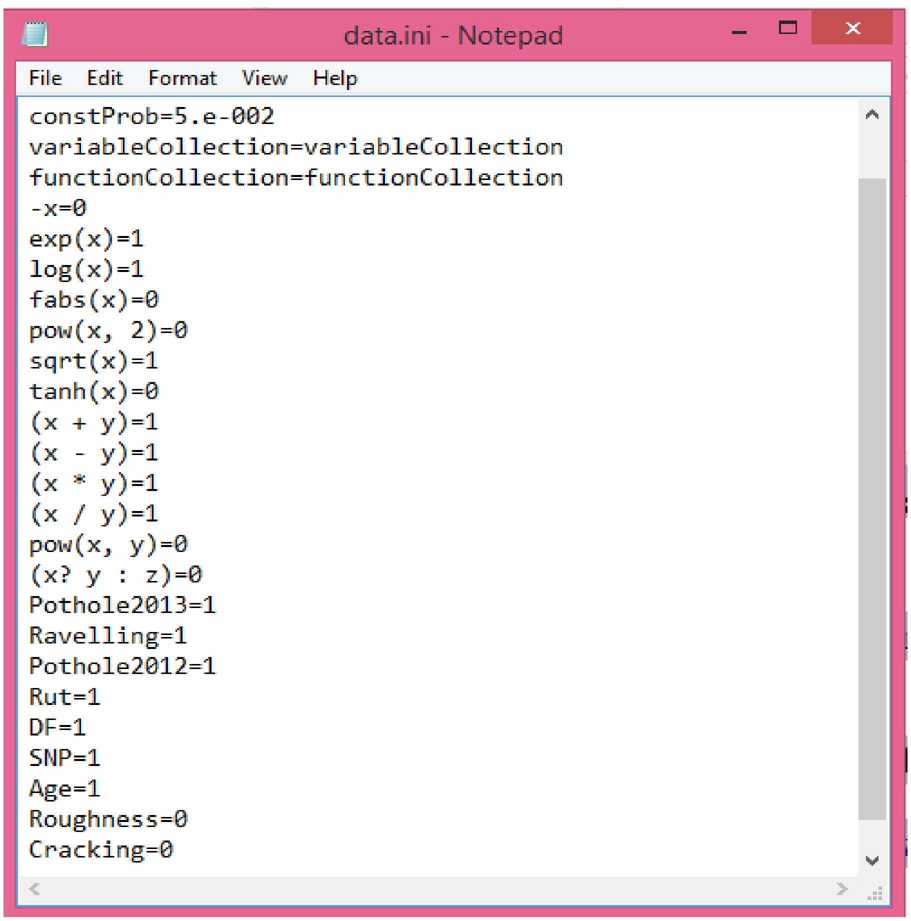


Fig. 5.9: Setting Input Parameters of ITable Pool

c) Change the Evolution Parameters

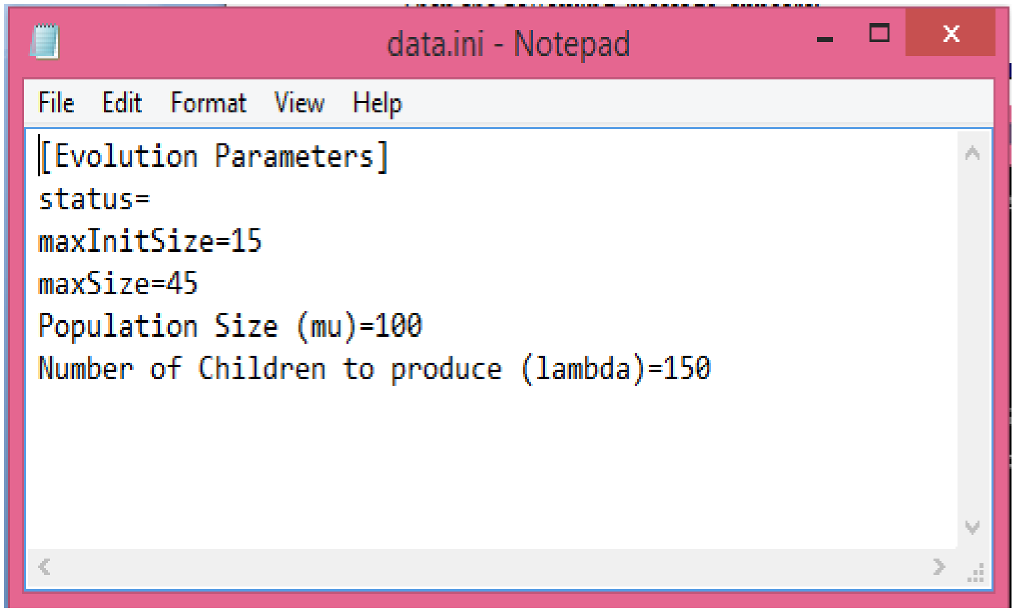


Fig. 5.10(a): Setting Evolution Parameters

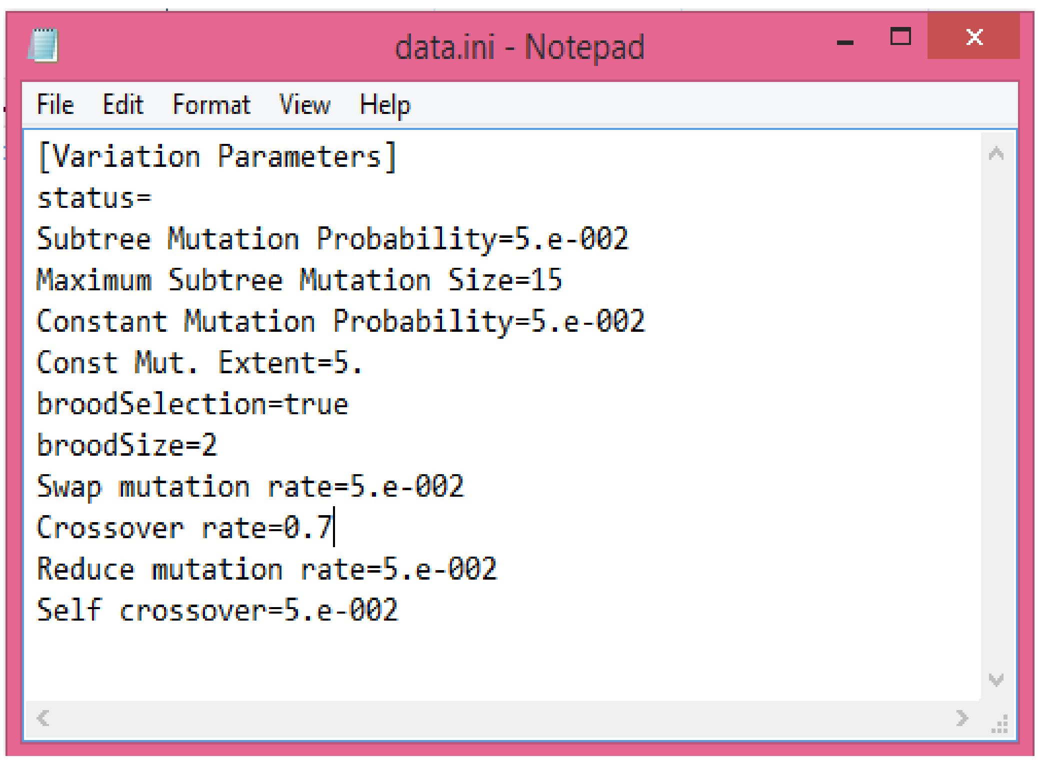


Fig. 5.10(b): Setting Evolution Parameters

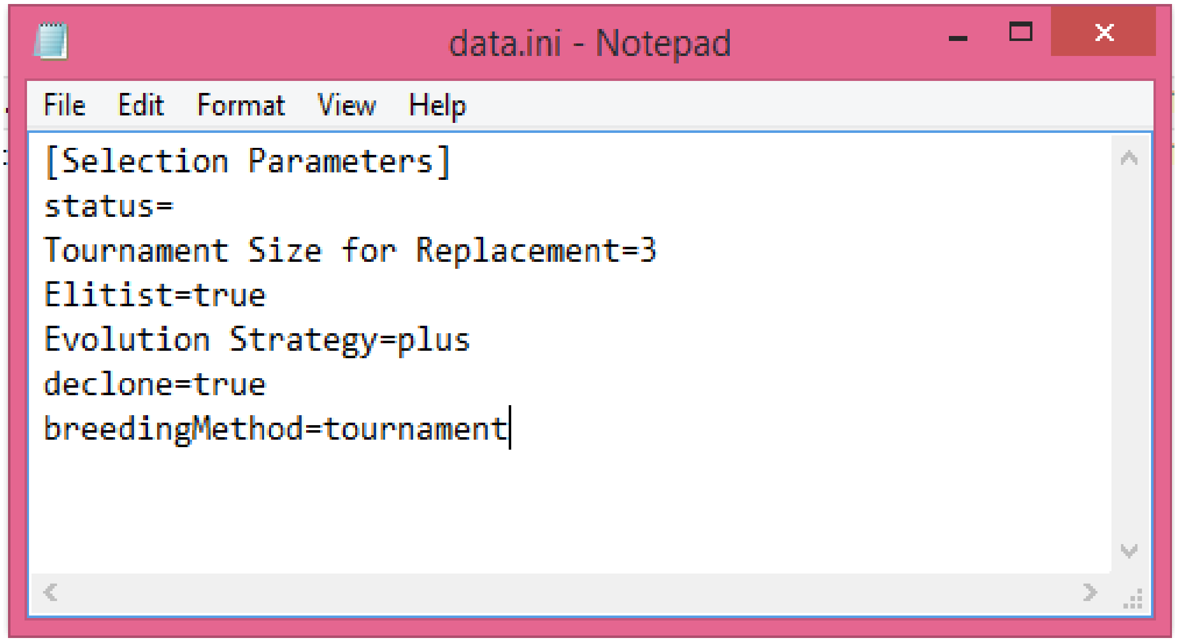


Fig. 5.10(c): Setting Evolution Parameters

GPkernel will give this message : **All pools are now set properly. You can now set the "Run experiments On Startup" variable on true**

[17] Change the parameters, **TimeOut=_** , and **Number of Experiments**= **_** in **…\pool\data.ini** , ***gpkernel*** *project1****.ini fromdir***

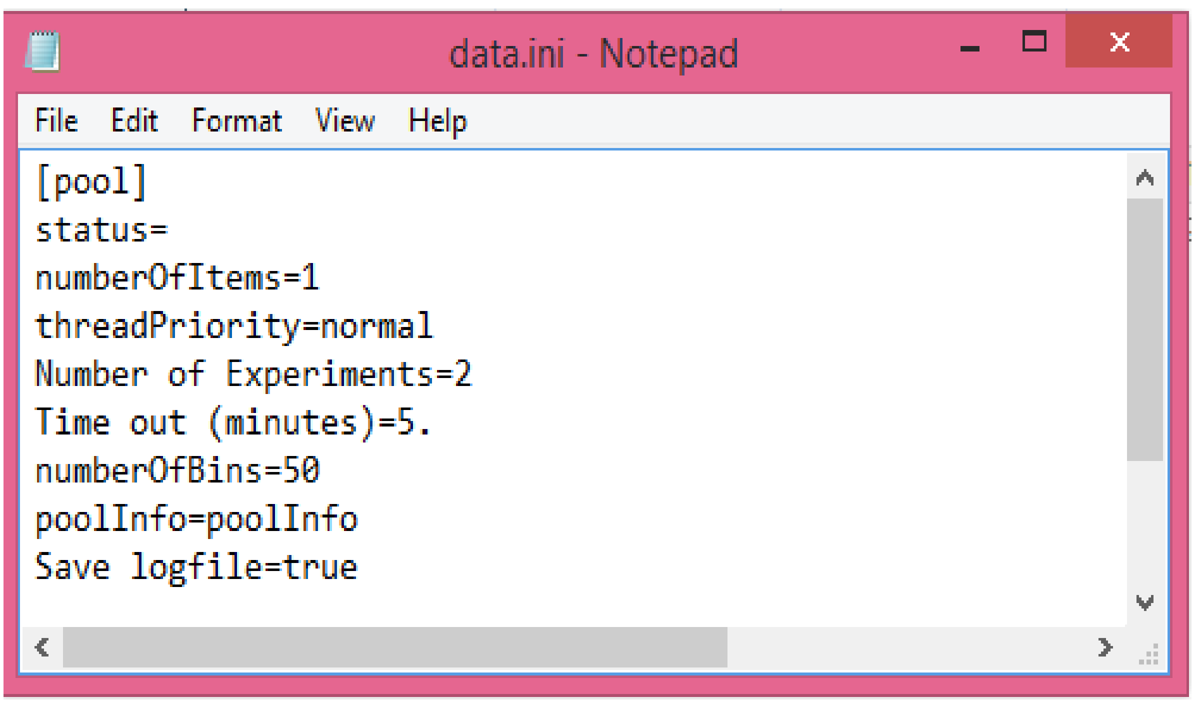


Fig. 5.11: Setting the Run Criteria for an Experiment

[18] In the **…*project1*.d2k\data.ini** file set “Run experiments On Startup” variable on true,

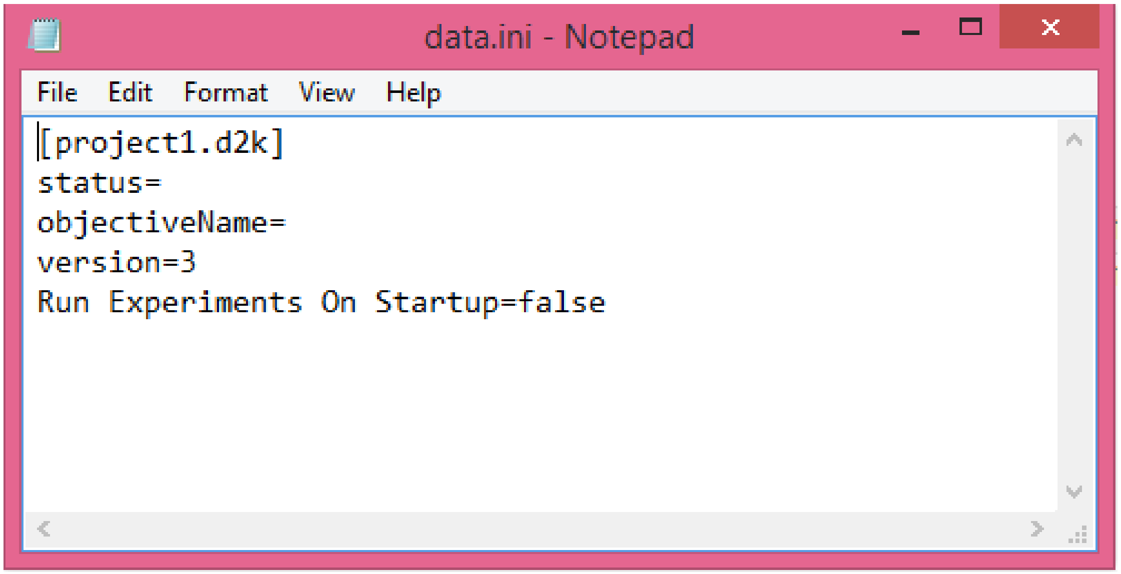


Fig.5.12: Setting Parameter to Run Experiments

[19] The program should now start running.

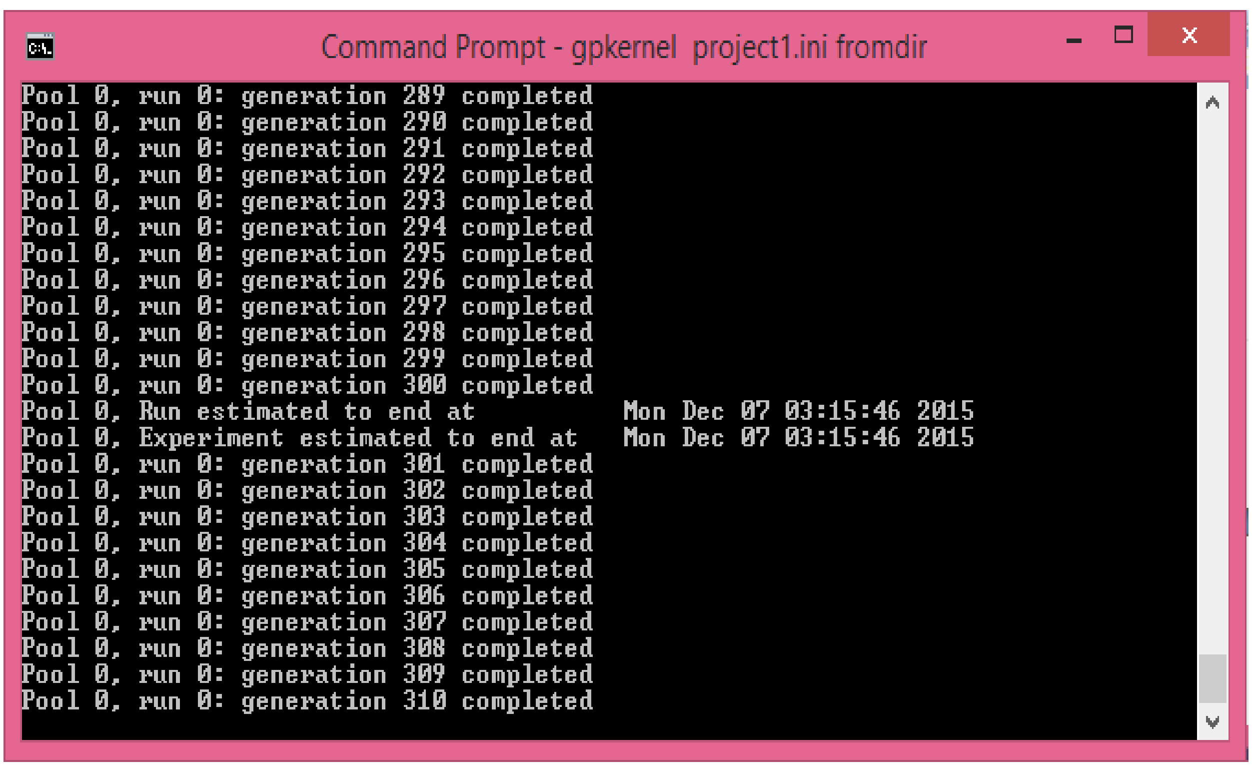


Fig. 5.13(a): GP Kernel at Running Stage of an Experiment showing Completion of 310 Generations

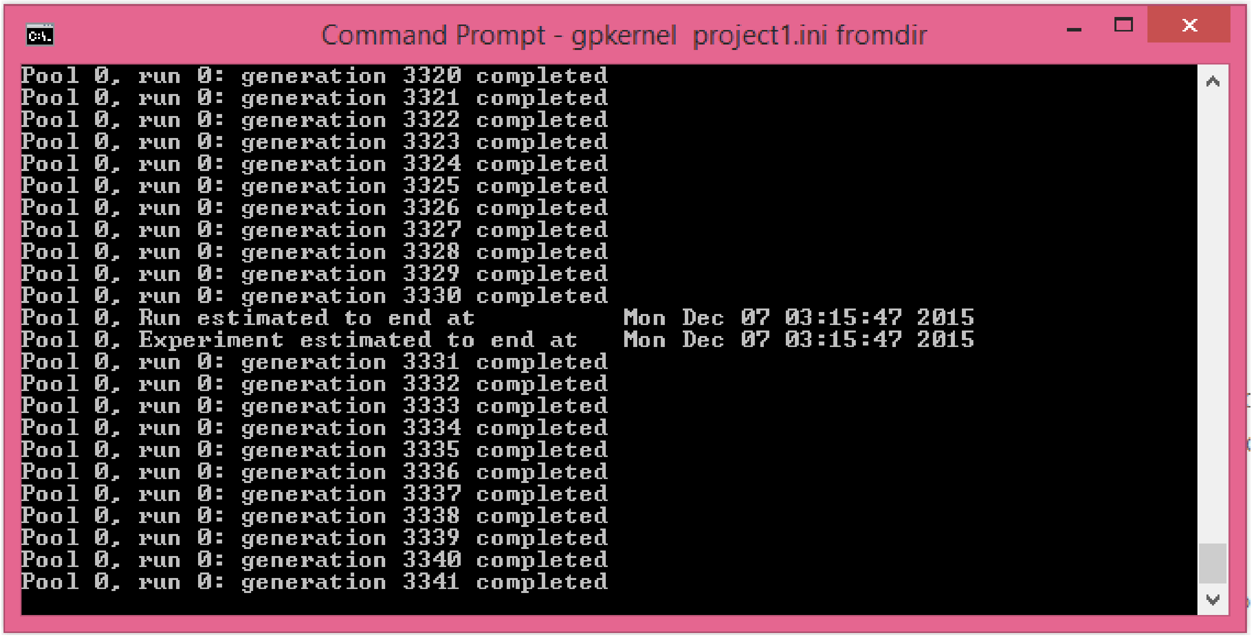


Fig. 5.13(b): GP Kernel at Running Stage of an Experiment showing Completion of 3341 Generations

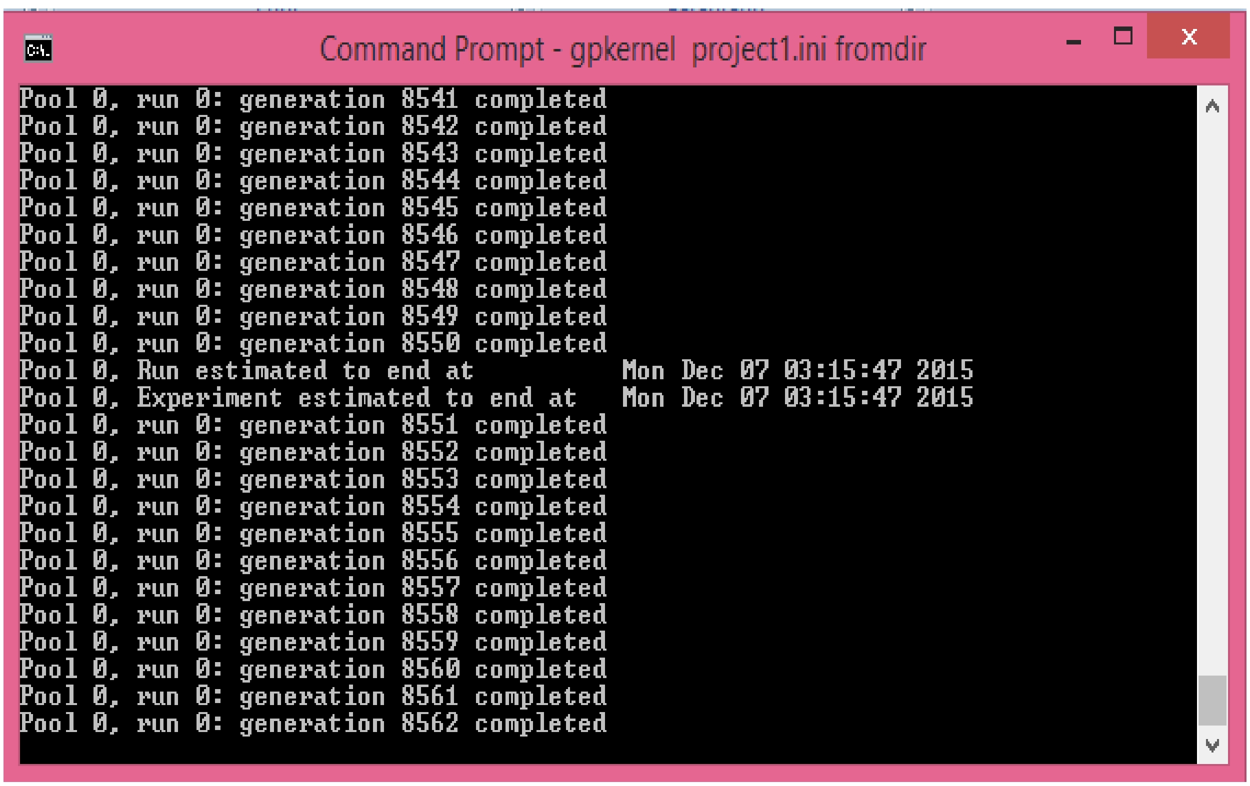


Fig. 5.13(c): GP Kernel at Running Stage of an Experiment showing Completion of 8562 Generations

[20] Completion of Experiment

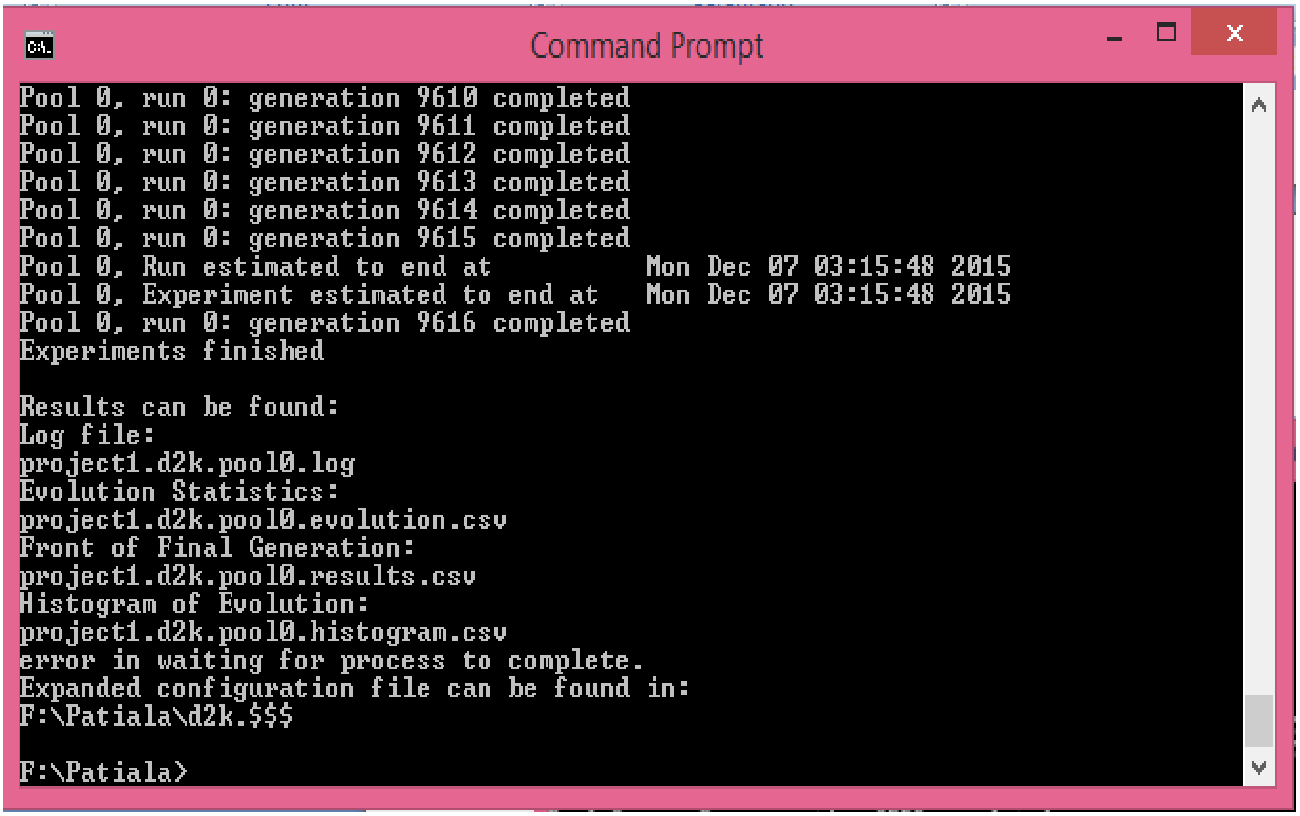


Fig. 5.14: GP Kernel at Completion Stage of an Experiment

5.4 DEVELOPMENT OF GP MODEL

The dataset used for GP model development is same as used in Chapter 4 for the development of HDM models. The control parameters as given in Koza (1992) have been investigated in this study. The population size (*mu*) and the number of children produced (*lambda*) have been taken 100 and 150, respectively. As, larger is the number of generations, greater are the chances of evolving a solution, the number of generations has been taken as 100000. The values for the parameters, namely, crossover rate and mutation rate have been selected as 0.70 and 0.05, respectively, after experimentations. The values of other parameters, *i.e.*, training percentage, selection method and tournament size of substitution are taken as 75, 'tournament' and 3, respectively for the development of GP model. Function set (‘+, -, *, /’) has been taken for both the datasets. The architectural details of the selected GP model are given in Table 5.1.

Table 5.1: Architecture of GP Model

Parameters	Values	Description
Initial Population Size	Dataset	Dataset - 1 is of 16 instances consisting of data gathered in 2012 and 2013.
Function Set	+, -, *, /, sqrt	Set of functions used
Training percentage	75	---
Selection Method	Tournament	---
Tournament size of replacement	3	---
Maximum Generations	100000	Maximum number of iterations
Crossover	0.7	Probability of crossover
Mutation	0.05	Probability of mutation
mu	100	Population size
lambda	150	No. of children produced
Objectives	R^2	Co-efficient of determination
	RMSE	Root mean square error

5.4.1 Models generated using GP

In the GP model development, the addition is chosen as the linking utility. The prediction models generated using the GP are listed in Table 5.2 and some of the generations (out of 100000 for each model) generated by GP kernel are presented in Section 5.7. It consists of five models: Model1, Model2, Model3, Model4 and Model5 for Cracking, Ravelling, Potholes, Rutting and Roughness, respectively.

5.4.2 Results and Discussions

The results obtained from this approach have been used for the quantitative assessment of the model's predictive abilities and presented in Table 5.3. The data set gathered during the years 2012 and 2013 have been used for training models, *i.e.*, for the prediction of year 2013 pavement distress, the data set of year 2012 has been used. The post-regression fits for the training data set all the models (Model 1, Model 2, Model 3, Model 4 and Model 5) are presented in Figs. 5.15-5.19, respectively.

Table 5.2: GP Models for Progression of Cracking, Potholes, Ravelling, Rutting and Roughness for Urban Roads

Model 1 (Cracking Progression)	$$CA_j = \frac{1}{MSN_i}\left((MSN_i \times CA_i) + \frac{e^{\left(\frac{CA_i \times e^{-ESA_i}}{AGE_i}\right)}}{AGE_i} + \frac{2MSN_i + AGE_i + e^{ESA_i}}{CA_i} + 1\right)$$ *Where, CA_j is cracking of next year, CA_i is cracking of previous year, MSN_i is modified structural number of previous year, AGE_i is age of pavement before the start of analysis year, ESA_i is the number of equivalent standard axle repetitions in the analysis year (in millions).*
Model 2 (Ravelling Progression)	$$RA_j = 1 + RA_i + \frac{AGE_i(1 + ESA_i) + 2\left(RA_i + e^{\sqrt{AGE_i}}\right)}{RA_i(ESA_i + AGE_i)} + \tanh\left(AGE_i^2\left((AGE_i \times ESA_i) - RA_i\right)\right)$$ *Where, RA_j is ravelling area of next year and RA_i is ravelling of previous year, AGE_i is age of pavement before the start of analysis year, ESA_i is the number of equivalent standard axle repetition in the analysis year (in millions).*
Model 3 (Potholes Progression)	$$POT_j = tanh\left(e^{tanh(CA_i)} + RA_i + POT_i\right) + POT_i - ESA_i - tanh\left(POT_i - tanh\left(POT_i - tanh\left(\sqrt{tanh(AGE_i)}\right) - AGE_i\right)\right)$$ *Where,POT_j is Pothole of next year (number per km),POT_i is Pothole of next year (number per km), CA_i* is cracking of previous year, RA_i is ravelling area of previous year, *AGE_i is age of pavement before the start of analysis year, ESA_i is the number of equivalent standard axle repetition in the analysis year (in millions).*
Model 4 (Rutting Progression)	$$RD_j = RD_i + DF + \tanh\left(\frac{RD_i(MSN - DF - 1)}{\log\left(\frac{MSN}{ESA_i}\right) + CA_i + AGE_i + \frac{RD_i}{2MSN + \log(MSN)}}\right)$$ *Where, RD_j is rutting of next year, RD_i is rutting of previous year, MSN_i is modified structural number of previous year, AGE_i is age of pavement before the start of analysis year, DF is the drainage factor, CA_i* is cracking of previous year, *ESA_i is the number of equivalent standard axle repetitions in the analysis period (in millions).*
Model 5 (Roughness Progression)	$$IRI_j = 1.254\left(\frac{(ESA_i \times AGE_i \times IRI_i)}{(ESA_i \times RD_i \times dNPT \times AGE_i) + (12.048 \times IRI_i) + ({ESA_i}^3 \times AGE_i)} + (IRI_i)\sqrt{ESA_i}\right)$$ *Where, IRI_j is roughness of next year, IRI_i is roughness of previous year, ESA_i is the number of equivalent standard axle repetitions in the analysis year (in millions), AGE_i is age of pavement before the start of analysis year, dNPT is change in the number of potholes during analysis year, RD_i is rut depth in the previous year.*

It can be seen from Fig. 5.15 that Model1 (Cracking Progression), the value of R^2 is 95.5% and for Model4 (Rutting Progression; Fig. 5.18), the value of R^2 is 97.2% with Root Mean Square Error (RMSE) of 0.48 and 0.27, respectively. For Model2 (Ravelling Progression) and Model3 (Pothole Progression), the values of R^2 are 83.5% and 89.5%, respectively. The value of RMSE in Model2 and Model3 are 0.53 and 0.93, respectively. The post- regression fits of Model2 and Model3 are presented in Fig. 5.16 and Fig. 5.17, respectively. However, from Fig. 5.19, it can be observed that for Model5 *i.e.*, Roughness Progression, the value of R^2 is 79.4% with the value of RMSE of 0.04. It can be observed from Figs. 5.15-5.19 that the deviation can be noticed between observed and predicted values because of modeling approach adopted. But, this variation is quite reasonable for the urban road section of different age and traffic loading conditions.

Table 5.3: Results of Training and Validation of Proposed Models

Data Set	Model	R^2 (%)	RMSE
Training Dataset (2013)	Model1	95.5	0.48
	Model2	83.5	0.53
	Model3	89.5	0.93
	Model4	97.2	0.27
	Model5	79.4	0.04
Validation Dataset (2014)	Model1	77.2	0.60
	Model2	78.1	0.62
	Model3	83.8	0.71
	Model4	80.0	0.86
	Model5	80.8	0.76
Validation Dataset (2015)	Model1	75.4	0.89
	Model2	74.8	0.90
	Model3	89.9	0.70
	Model4	80.9	0.90
	Model5	73.0	0.09

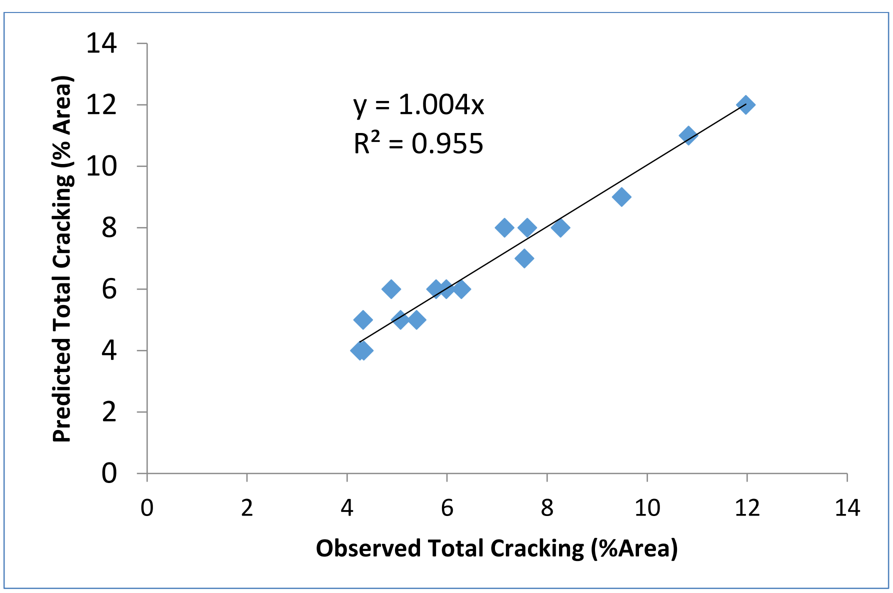


Fig. 5.15: Scatter Plot between Observed vs Predicted Total Cracking for Training

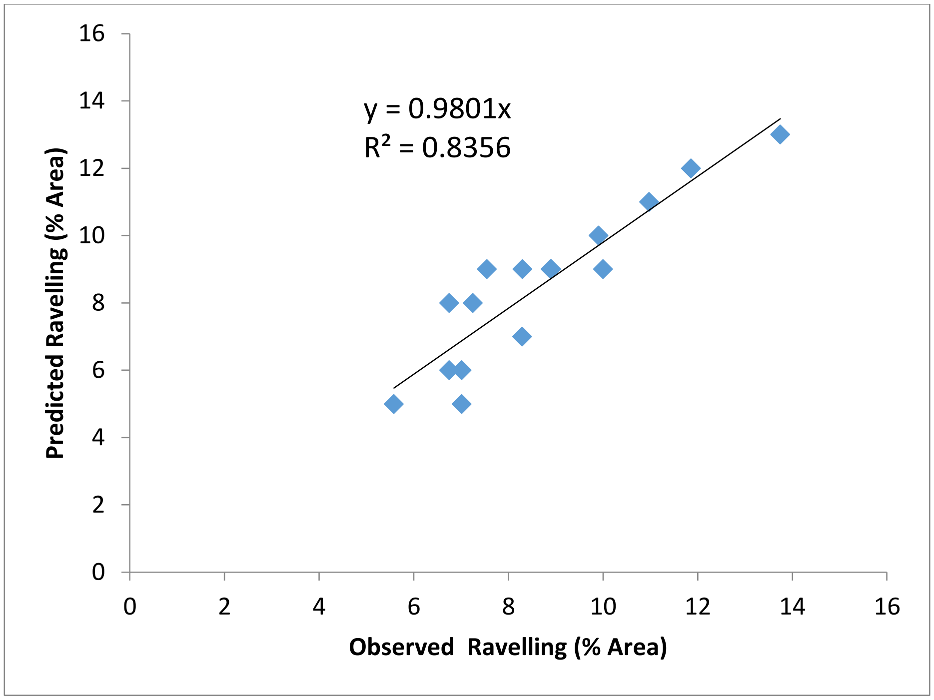


Fig. 5.16: Scatter Plot between Observed vs Predicted Ravelling for Training

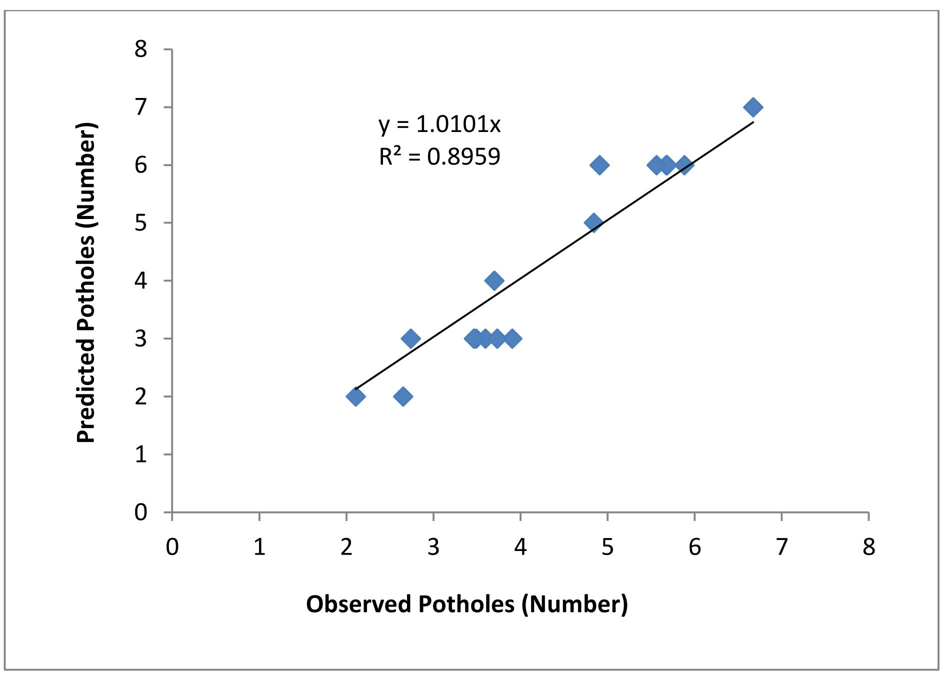


Fig. 5.17: Scatter Plot between Observed vs Predicted Potholes for Training

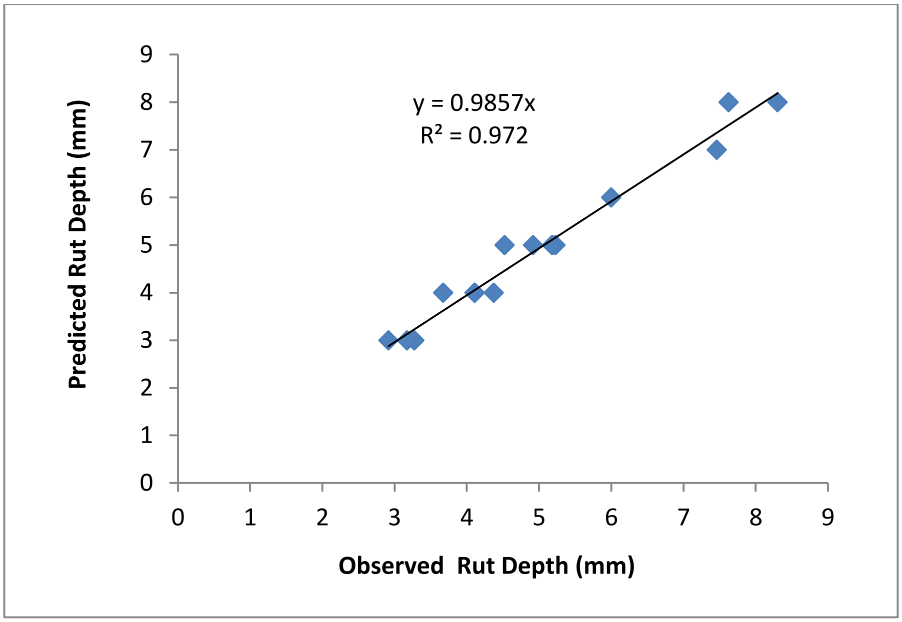


Fig. 5.18: Scatter Plot between Observed vs Predicted Rutting for Training

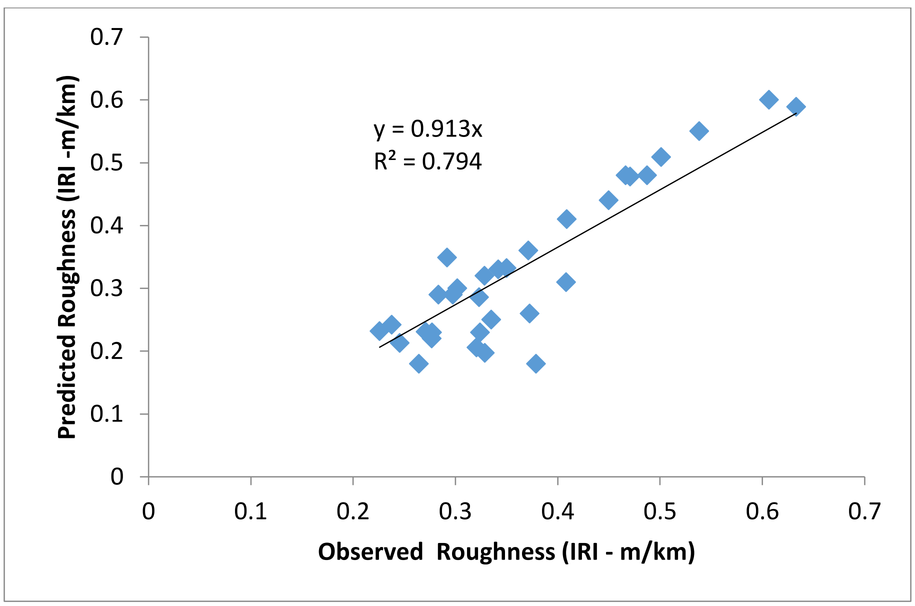


Fig. 5.19: Scatter Plot between Observed vs Predicted Roughness for Training

5.4.3 Validation of GP Models

To further test the efficacy and reliability of the models, the data sets collected during the years 2014 and 2015 have been used for the validation purposes. For the prediction of pavement distress of year 2014, the data gathered during year 2013 has been used and for the prediction of pavement distress of year 2015, the data gathered during year 2014 has been used. The post-regression fits for the validation data sets (2014-2015) all the models (Model1, Model2, Model3, Model4 and

Model5) are presented in Figures 5.20-5.29, respectively. The value of R^2 obtained for the cracking progression using Model1 (year 2014) is 77.2% and for the (year 2015), it is 75.4% with value of RMSE 0.60 and 0.89, respectively. For ravelling progression (Model2) of year 2014 and for year 2015, the values of R^2 obtained are 78.1% and 74.8, respectively. The value of RMSE for Model2 for validation data set of year 2014 and year 2015are 0.89 and 0.9, respectively. The values of R^2 obtained for pothole progression using Model3 (years 2014 and year 2015) are 83.8% and 89.9%, respectively, and the value of RMSE of Model3 for validation data set is 0.71 and 0.70, respectively. Model4 is developed for rutting progression and the values of R^2 obtained are 80% and 80.9%, for year 2014 and year 2015, respectively. The values of RMSE of Model3 for the validation data set is 0.86 (year 2014) and 0.90 (year 2015). Model5 has been used to obtain the roughness progression and the values of R^2 obtained for year 2014 and year 2015 are 80.8% with RMSE 0.76 and 73.0% with RMSE 0.09, respectively. All the GP models have been predicting with good competence for both the data sets (2014 and 2015). The results are revealing that these GP models can be applied successfully to the roads of Patiala City, Punjab, India.

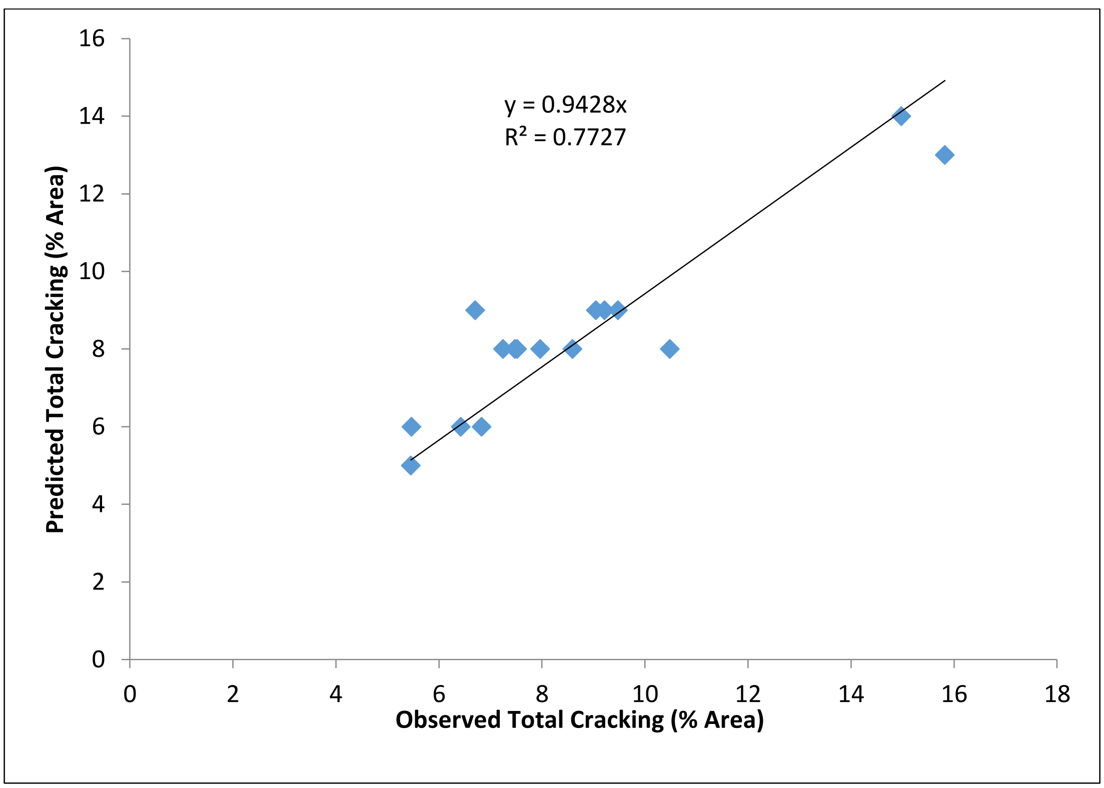


Fig. 5.20: Scatter Plot between Observed vs Predicted Total Cracking for Validation (2014)

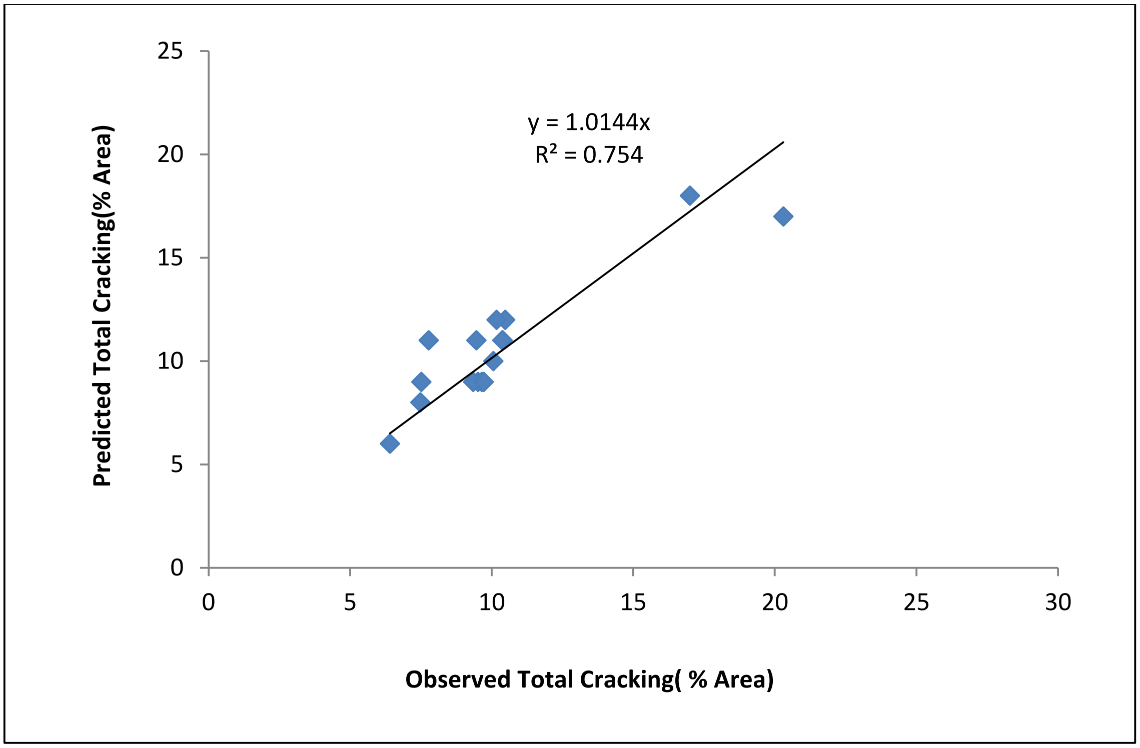


Fig. 5.21: Scatter Plot between Observed vs Predicted Total Cracking for Validation (2015)

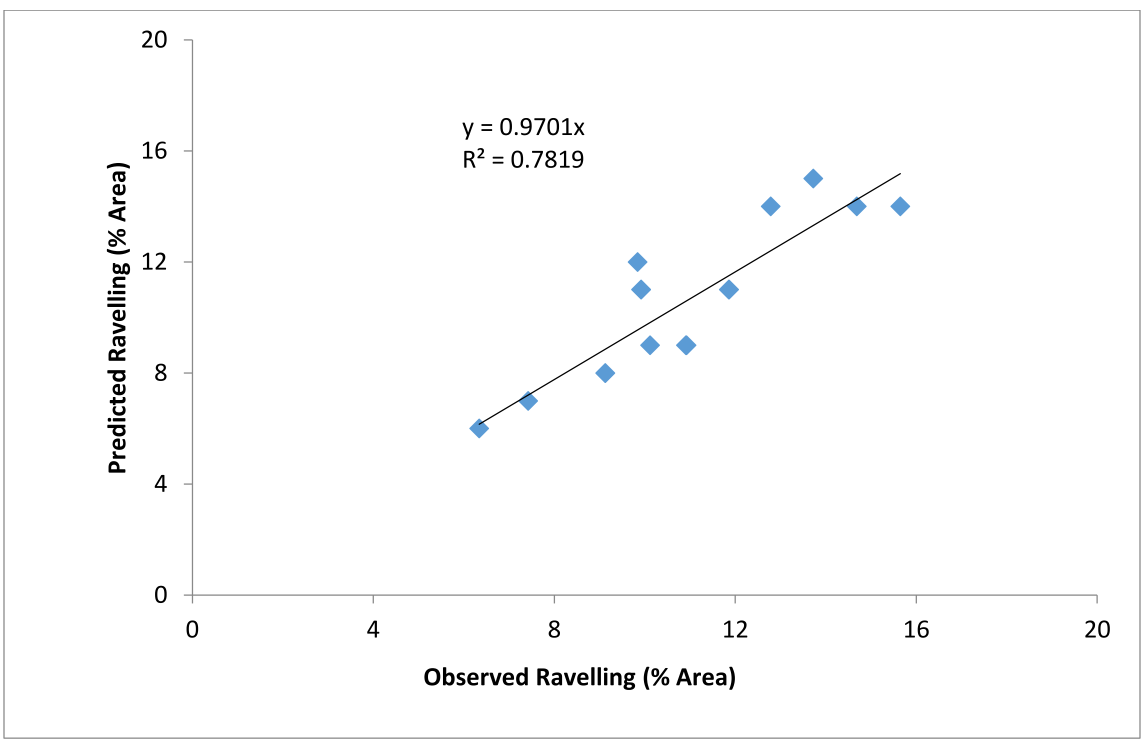


Fig. 5.22: Scatter Plot between Observed vs Predicted Ravelling for Validation (2014)

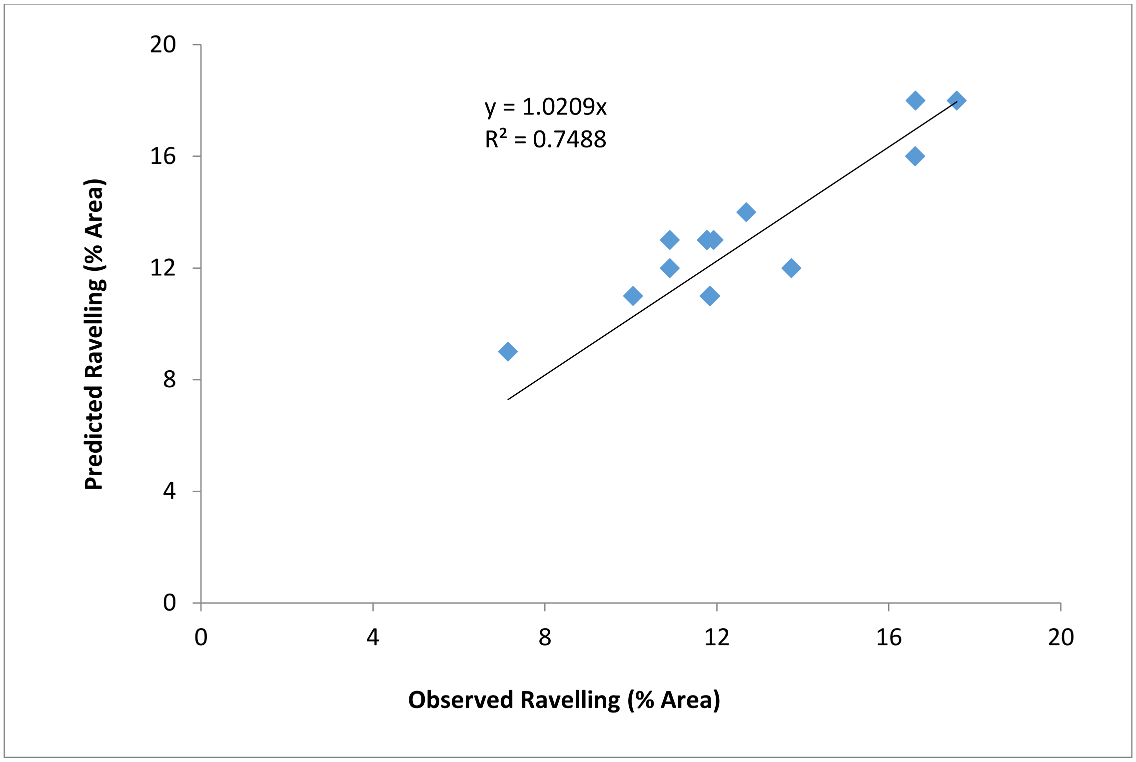


Fig. 5.23: Scatter Plot between Observed vs Predicted Ravelling for Validation (2015)

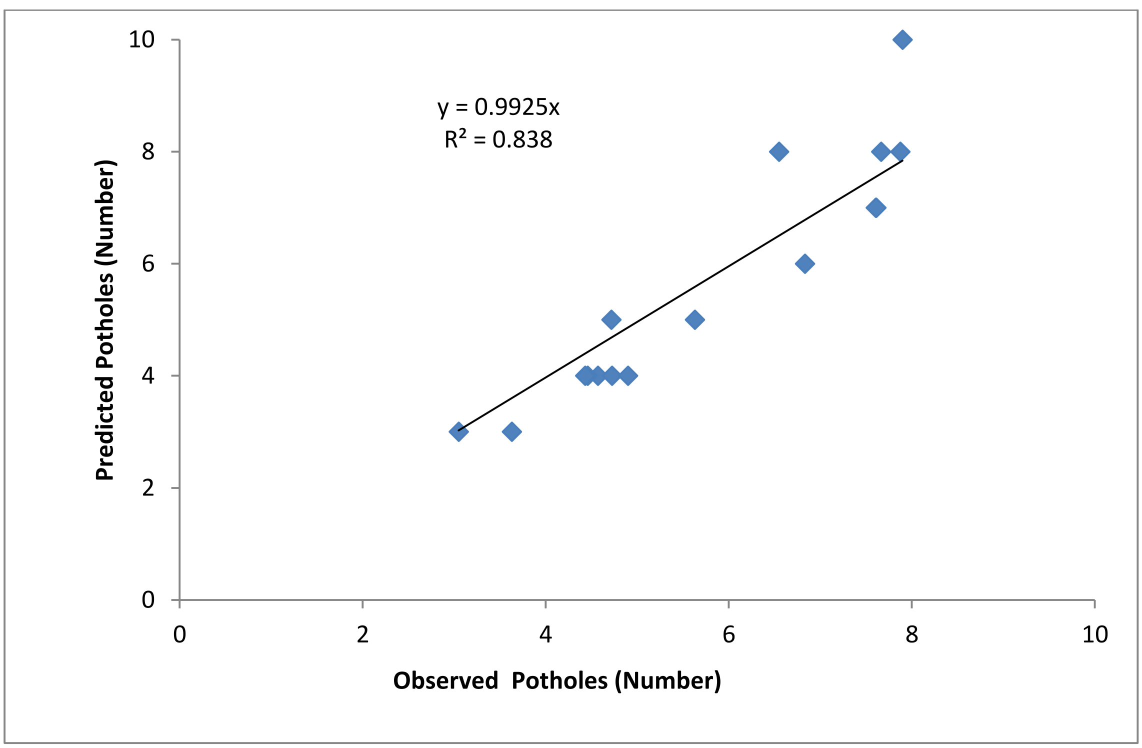


Fig. 5.24: Scatter Plot between Observed vs Predicted Potholes for Validation (2014)

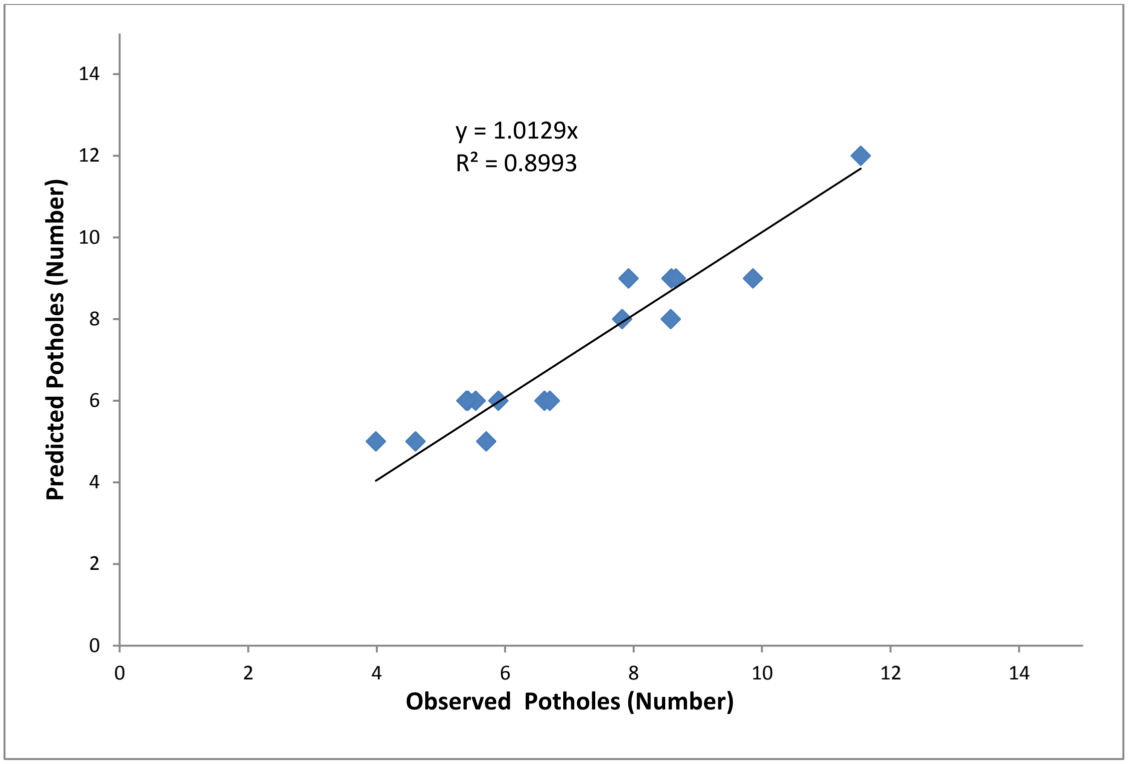


Fig. 5.25: Scatter Plot between Observed vs Predicted Potholes for Validation (2015)

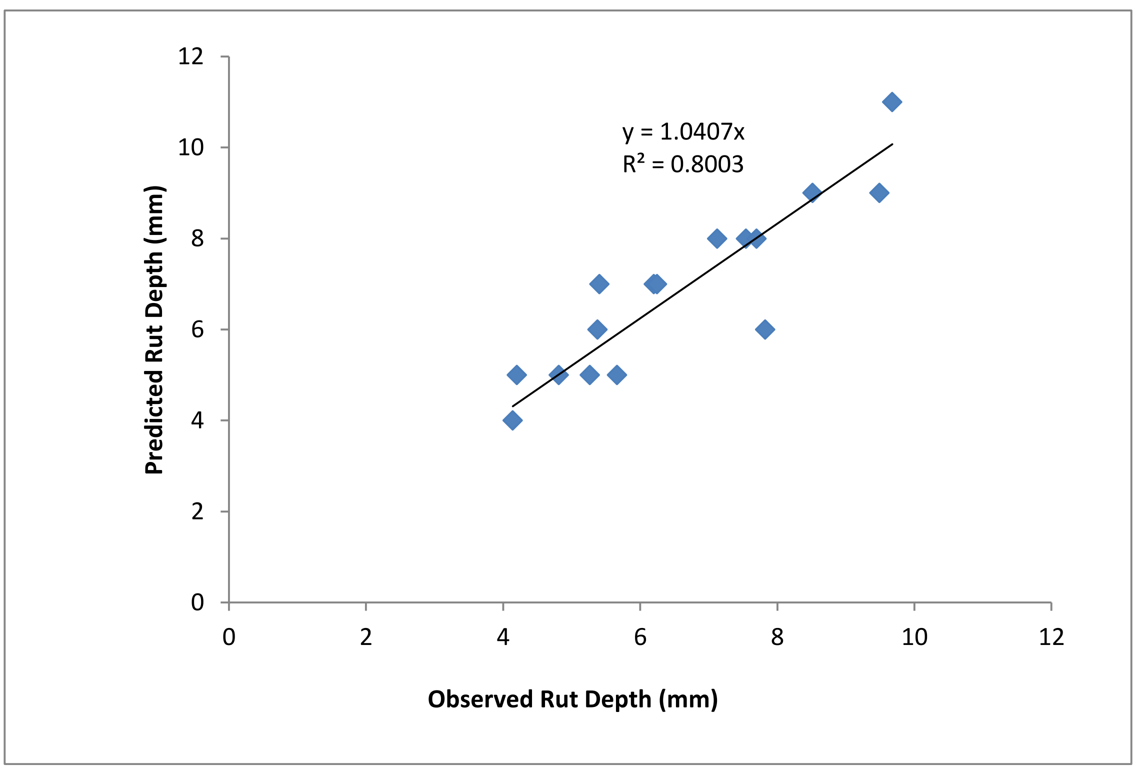


Fig. 5.26: Scatter Plot between Observed vs Predicted Rutting for Validation (2014)

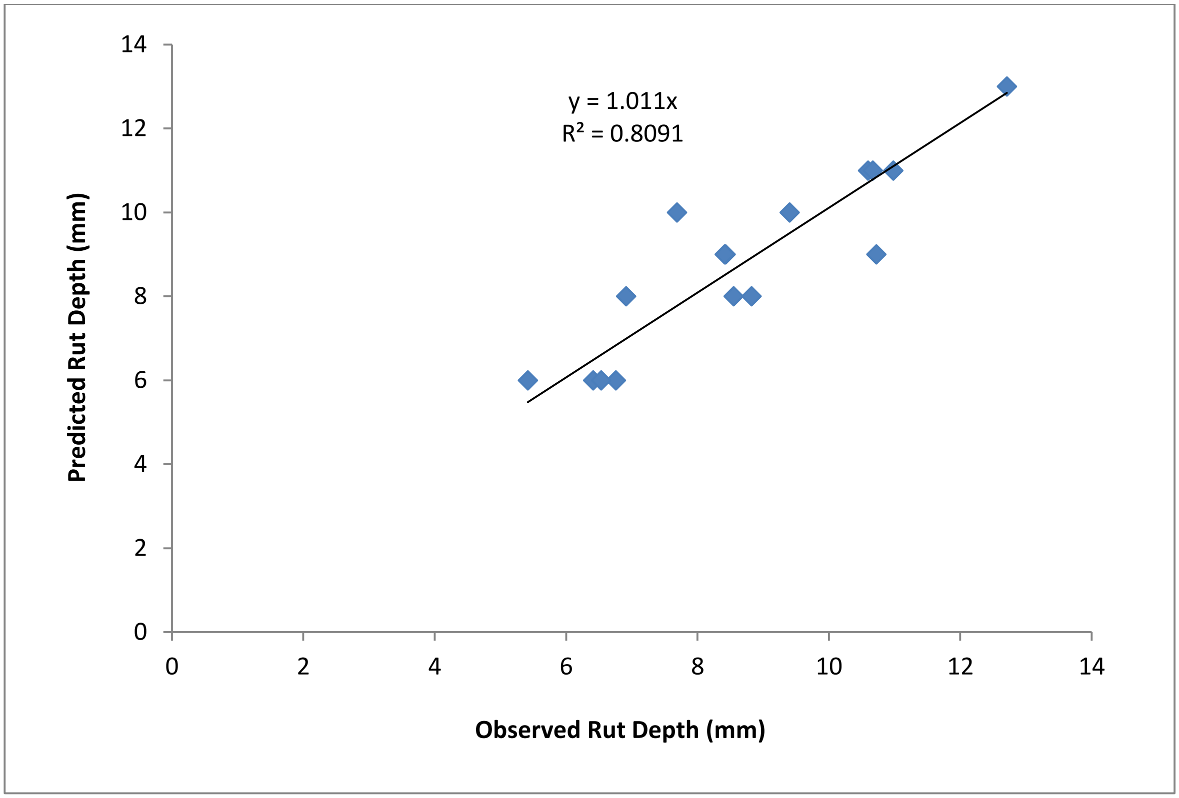


Fig. 5.27: Scatter Plot between Observed vs Predicted Rutting for Validation (2015)

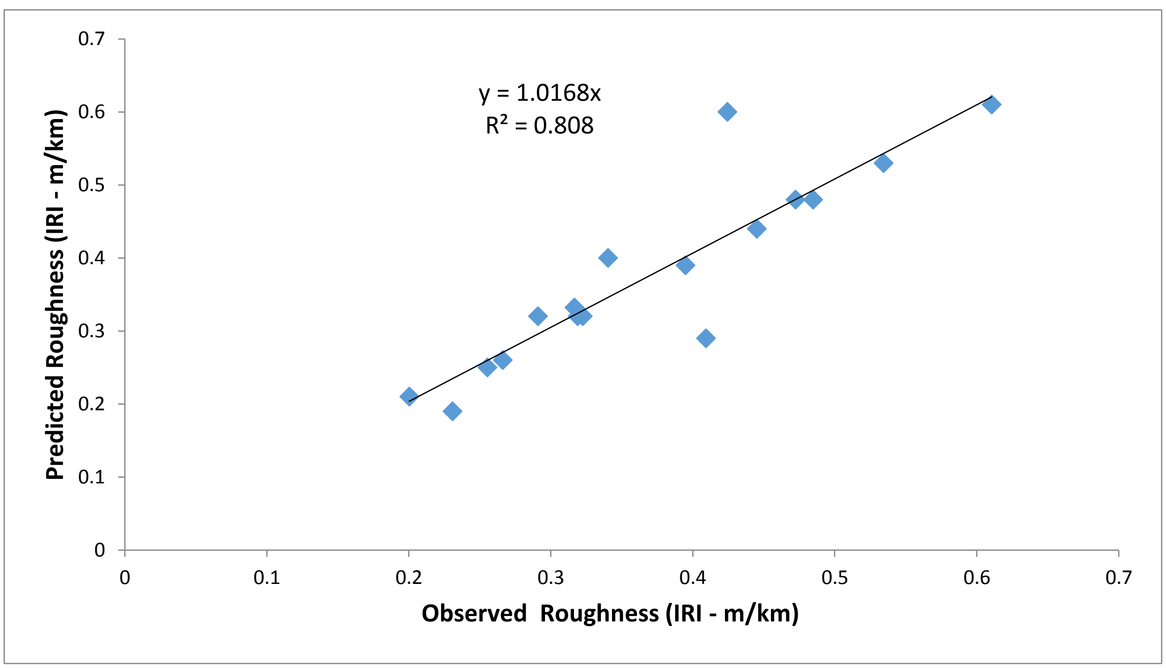


Fig. 5.28: Scatter Plot between Observed vs Predicted Roughness for Validation (0.1* IRI in 2014)

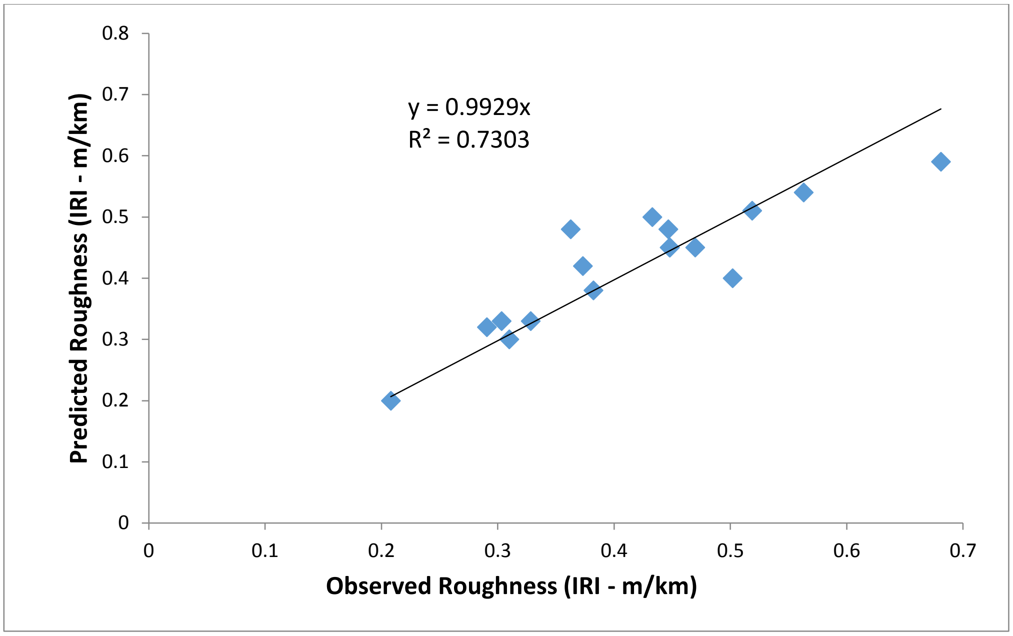


Fig. 5.29: Scatter Plot between Observed vs Predicted Roughness for Validation (0.1* IRI in 2015)

5.4.4 Conclusions

- The objective of this study was to explore the applicability of GP models for pavement distress. Five Models have been developed for Cracking Progression (Model1), Ravelling Progression (Model2), Pothole Progression (Model3), Rutting Progression (Model4) and Roughness Progression (Model5). The data collected during year 2012 to year 2015 on the 16 selected roads of Patiala, Punjab, India has been used for the development of these models.
- We can say that GP has built a good correlation between observed and predicted values and the parameters (like cracking, ravelling, pothole, rutting and roughness) that have been taken in the present study are sufficient for the prediction of pavement distress.
- These models can be applied to other city roads with a range of traffic varying from 0.1 to 0.85 equivalent standard axle repetitions in the initial analysis year and *MSN* in the range of 2 to 4.5.
- As an outcome, we can say that GP models provide good results for the prediction of pavement distress and may serve as a predictive model for the prediction of pavement

distress for all the cities having homogeneous traffic and climate conditions like Patiala, Punjab, India.

5.5 NEURAL NETWORK MODELS

Neural network modeling technique has several favorable features such as competence, generalization and straightforwardness that makes it an attractive preference for modeling of intricate systems. A successful neural network model for the prediction of pavement distress requires a good conception of the effect of several internal parameters. For a feed-forward back-propagation network structure and training process, the important internal parameters include data preprocessing and presentation, initial synaptic weights, learning rate (*lr*), number of hidden layers and number of neurons in each hidden layer (*hn*), activation functions (AF) for hidden layers and the number of training epochs. In this work, a three layer feed-forward back-propagation neural network is developed through experimental investigations of various internal parameters to predict the pavement distresses. The neural network models proposed in this chapter are described in Fig. 5.30. Fig. 5.31 contains a detailed architecture of the neural network model used in this work.

In Fig. 5.15, x_i is the input variable, $(net)_j$ is the weighted sum of the j^{th} neuron for the input received from the preceding layer with n neurons, w_{ij} is the weight between the j^{th} neuron of the current layer and the i^{th} neuron of the preceding layer. Output of j^{th} neuron is calculated by applying activation function (AF) on $(net)_j$.

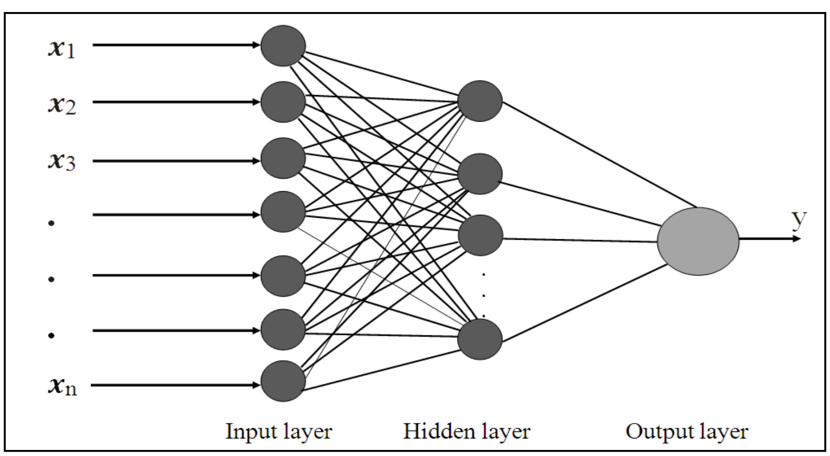


Fig. 5.30: Structure of Neural Network Model with an Input Layer, a Hidden Layer and an Output Layer

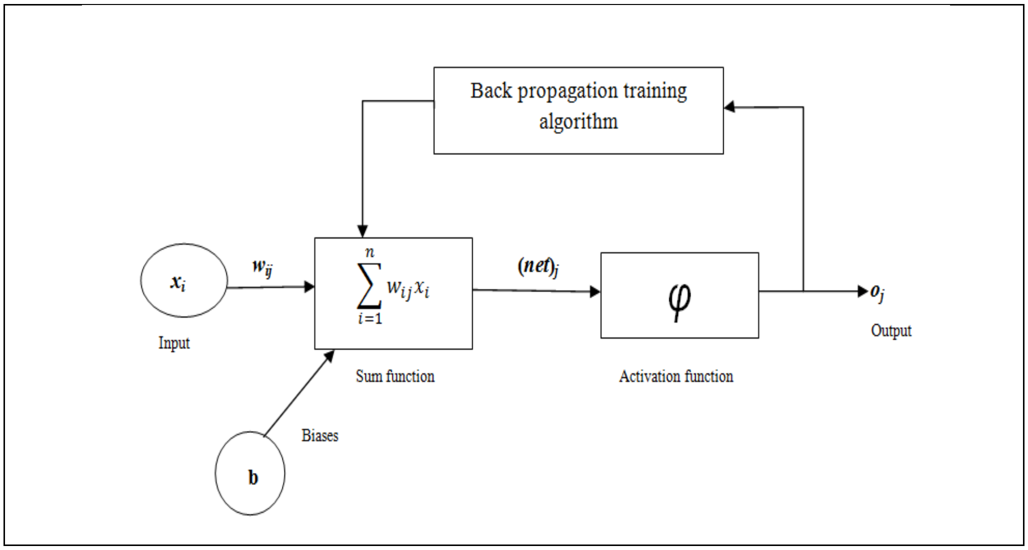


Fig. 5.31: Architecture of the Developed Neural Network Model

5.5.1 Development of Neural Network Model

Table 5.4 depicts the values of parameters used in pavement distress model. Experiments have been carried out using training functions trainlm() and two AFs, tan-sigmoid and linear. The values of *lr*, *goal* and *hn* for hidden layer has been taken as 0.01, 0.000001 and 50, respectively. MATLAB routine post-regression (postreg()) has been used to measure the network performance, which implements a regression analysis between network response and corresponding targets.

Table 5.4: Parameters used to Develop Neural Network Architecture

Parameters	Values	Description
AF-1	tan-sigmoid	tansig(x) = $\frac{2}{1+e^{-2x}}$ -1
AF-2	linear	purelin(x) = x
Performance function	MSE	Performance function (Mean Square Error)
Net.trainparam.lr	0.01	Learning rate
Training Function	trainlm()	Levenberg–Marquardt (LM)
Net.trainparam.epochs	10000	Maximum number of epochs fixed in training
Net.trainparam.goal	0.000001	Performance goal
Net.trainparam.show	15	Epochs between displays
Number of hidden layer neurons	50	Number of neurons in the hidden layer
Number of output layer neurons	01	Number of neurons in the output layer

5.5.2 Results and Discussions

In this section, neural network models have been proposed to predict the pavement distress. We empirically investigated different architectural parameters such as the number of hidden neurons (*hn*), learning rate (*lr*), AFs, performance goal (*goal*) and epochs for the optimal values of parameters of neural network models and has been found trainlm() training function, with tan-sigmoid as AF gives the better results than other training functions . The results of experiments are presented in Table 5.5 and the post-regression fits for experiments are presented in Figs. 5.32 - 5.36. The values of R^2 are 75.34%, 53.87%, 74.82%, 80.28% and 52.27% for Model 6, Model7, Model8, Model9 and Model10, respectively. The values of RMSE are 1.6, 2.0, 1.2, 1.3 and 1.9 for Model 6, Model 7, Model 8, Model 9 and Model 10 respectively.

Table 5.5: Results of Validation Dataset for various Neural Network Models

Model	R^2 (%) (Coefficient of Determination)	Epochs required in training	RMSE (Root Mean Square Error)	Best linear fit given by post-regression (A = predicted distress, T = target distress)
Model 6 (Cracking Progression)	75.34	115	1.6	A = (0.75)T + (1.69) 2
Model 7 (Ravelling Progression)	53.87	156	2.0	A = (0.565) T + (4.8)
Model 8 (Pothole Progression)	74.82	103	1.2	A = (0.984) T + (0.359)
Model9 (Rutting Progression)	80.28	109	1.3	A = (0.718) T + (1.12)
Model 10 (Roughness Progression)	52.27	142	1.9	A = (1.29) T + (-0.896)

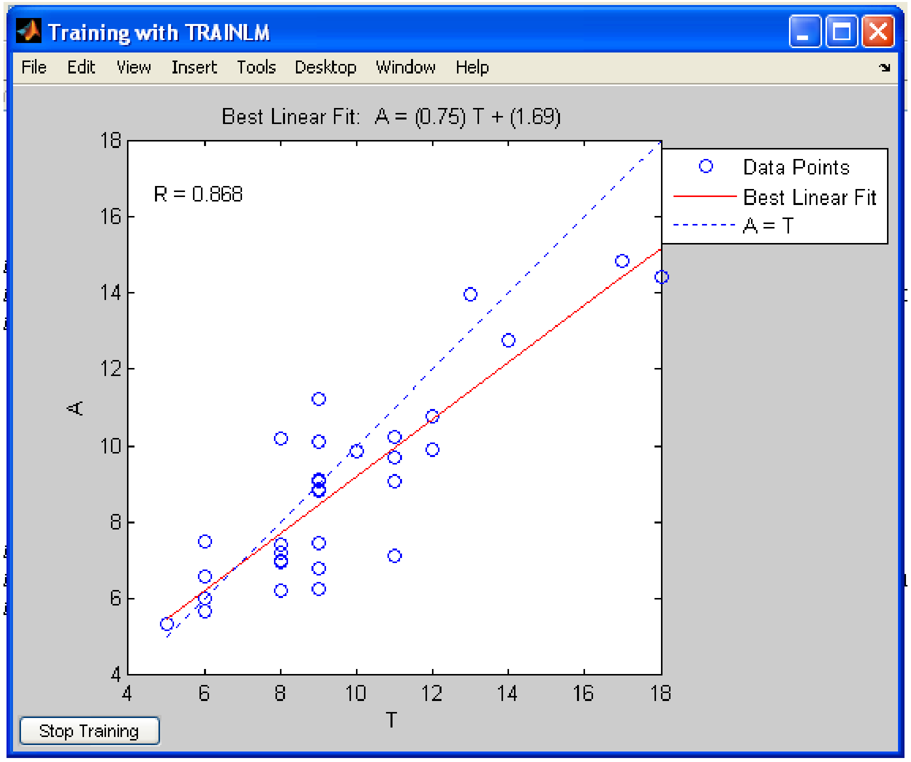


Fig. 5.32: Predicted Cracking Progression vs. Target Cracking Progression

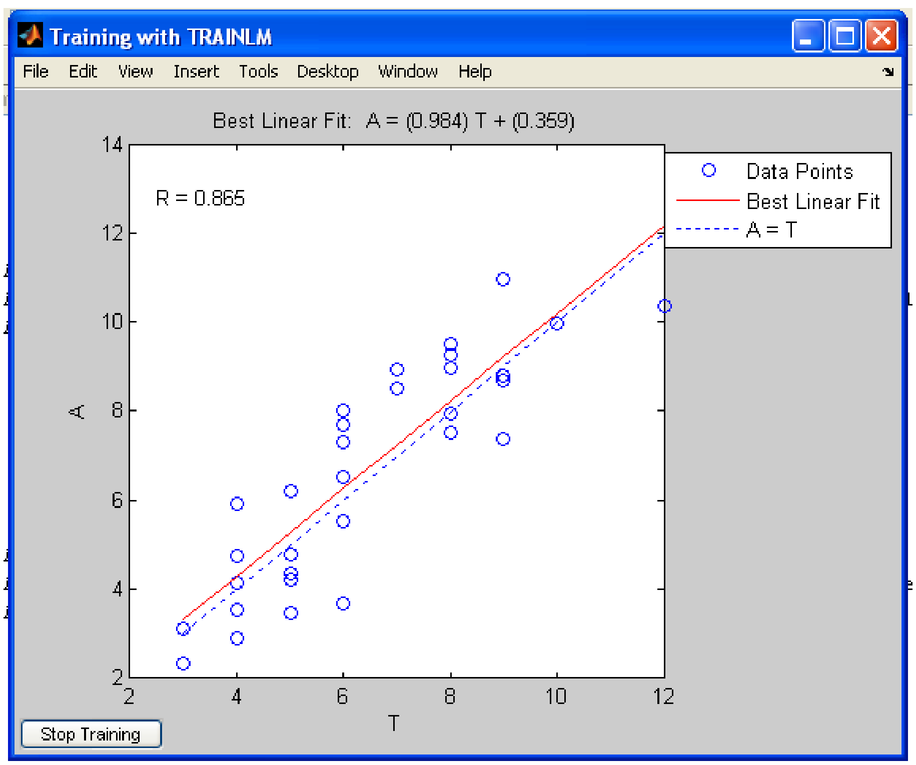


Fig. 5.33: Predicted Pothole Progression vs. Target Pothole Progression

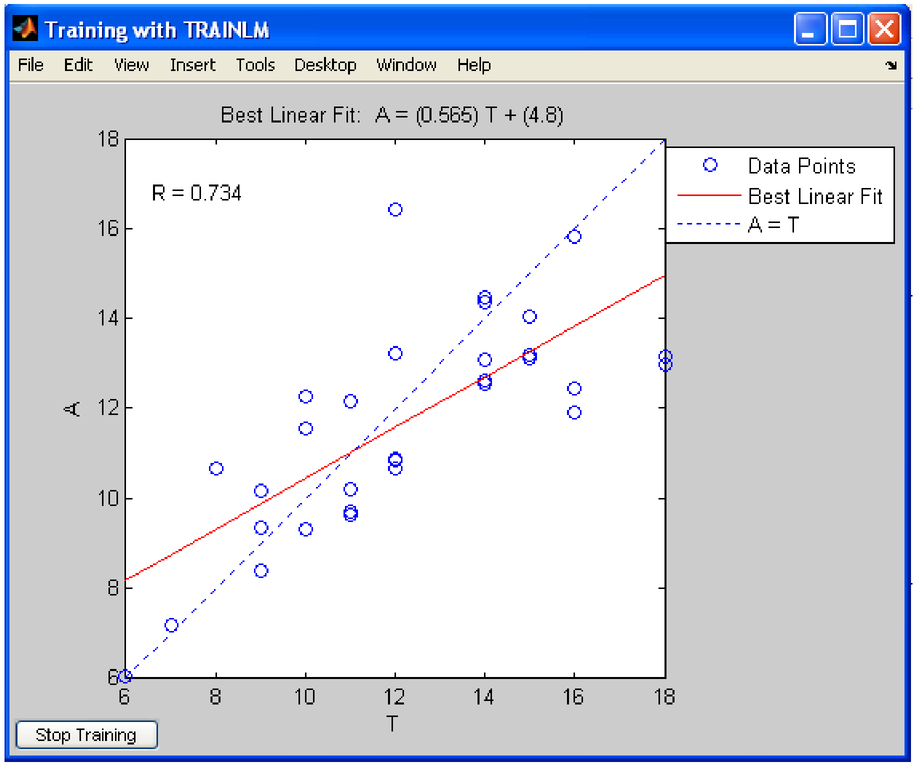


Fig. 5.34: Predicted Ravelling Progression vs. Target Ravelling Progression

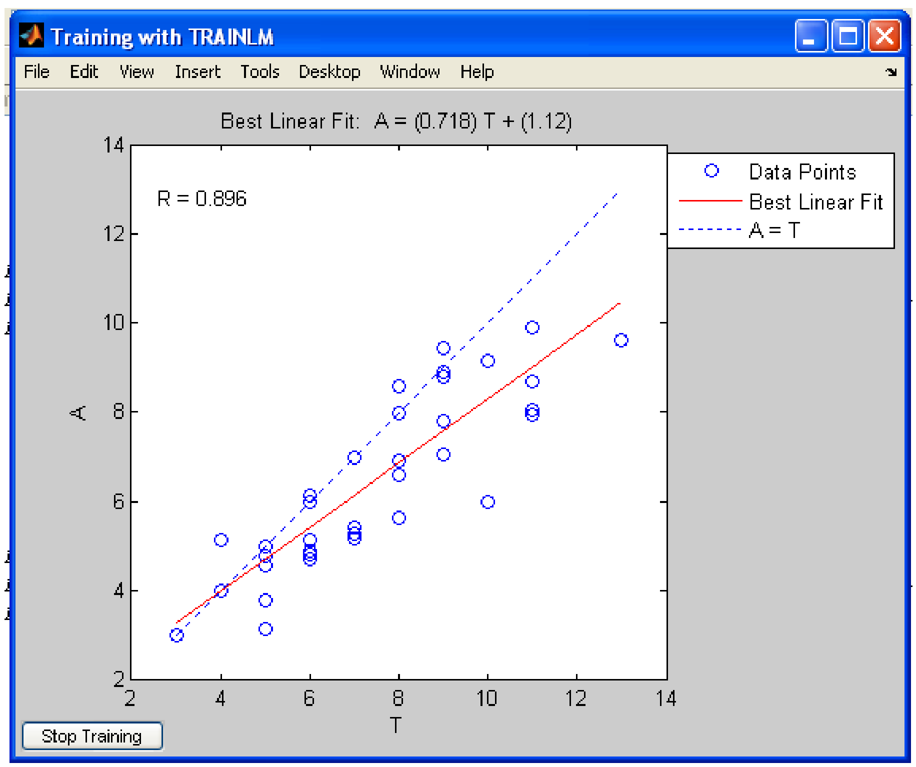


Fig. 5.35: Predicted Rutting Progression vs. Target Rutiing Progression

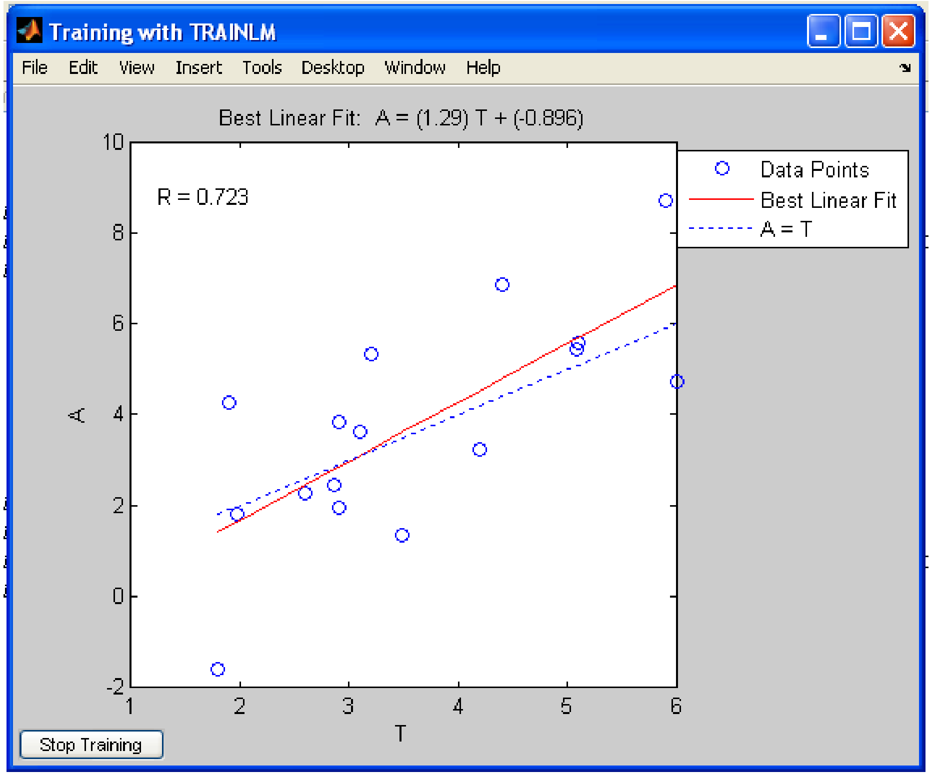


Fig. 5.36: Predicted Roughness Progression vs. Target Roughness Progression

5.5.3 Comparison of Neural Network Models with GP Models

The objective of the present study was to explore the applicability of suggested models, *i.e.*, neural network model and GP model for the prediction of pavement distress. This section presents the comparative investigation of results obtained from these approaches and quantitative assessment of the models' predictive abilities. In Section 5.4.2, the training function trainlm() has been used for the prediction of pavement distress; alongwith tan-sigmoid as AF has been used for evaluating the prediction accuracy parameters for neural network model. The results, as presented in Table 5.5, gives the values of R^2 for prediction of pavement distress. From these results, it can be observed that, in all the models(*i.e.*, Model6, Model7, Model8,Model9 and Model10) the value of R^2 is less than 80%. The prediction equations presented in Table 5.2 generated using GP model in Section 5.4. The values of R^2 for prediction of pavement distress obtained using GP models are provided in Table 5.3. From these results, it can be observed that, in all the models(*i.e.*, Model 1, Model 2, Model 3, Model 4 and Model 5) the value of R^2 is greater than 79.9%. The R^2 values for all the GP models are higher than in neural network models. From these results, it can be observed that, in all the models(*i.e.*, Model 6, Model 7, Model 8, Model 9 and Model 10) the value of R^2 is less than 80%.

5.5.4 Conclusions

Section 5.4.3 compared the results of neural network models with GP models. These results reveal that GP models have been predicting with higher values of R^2 as compared to neural network models. Therefore, it has been inferred that GP models are a good prediction model for the prediction of pavement distress for the roads of Patiala City, Punjab, India.

5.6 INTRODUCTION TO GEOGRAPHICAL INFORMATION SYSTEM (GIS)

To characterize the urban road network, a vast amount of data is required and the need is to continuously update the pavement deterioration. GIS plays a great role to PMMS, not only to display information, but also in analysis, planning and reporting. The pavement data can be integrated with GIS for quick and precise decision making regarding maintenance and rehabilitation.

An attempt has been made to integrate the network level PMM with GIS for the selected urban road network. ‘ArcGIS’ software which is commercially available for GIS applications has been used in the present study. With the help of GIS, we can display the present and future pavement conditions of the selected pavement sections and it can also provide information about the pavements that need immediate maintenance. Some of the important steps of ArcGIS are: a) Find the road network using Google map earth locations b) Extract and plot the selected road network c) Create the road network and d) Attach the attribute data to the spatial map. The Figs. 5.37-5.39 present the inputting the data screens and resultant screens. Fig. 5.40 presents to prioritization of selected roads of Patiala with their optimum M&R strategy and NPV/Cost Ratio. Fig. 5.41 presents progression of Roughness in the analysis period for various road sections. Fig. 5.42 presents RSL of selected urban road network.

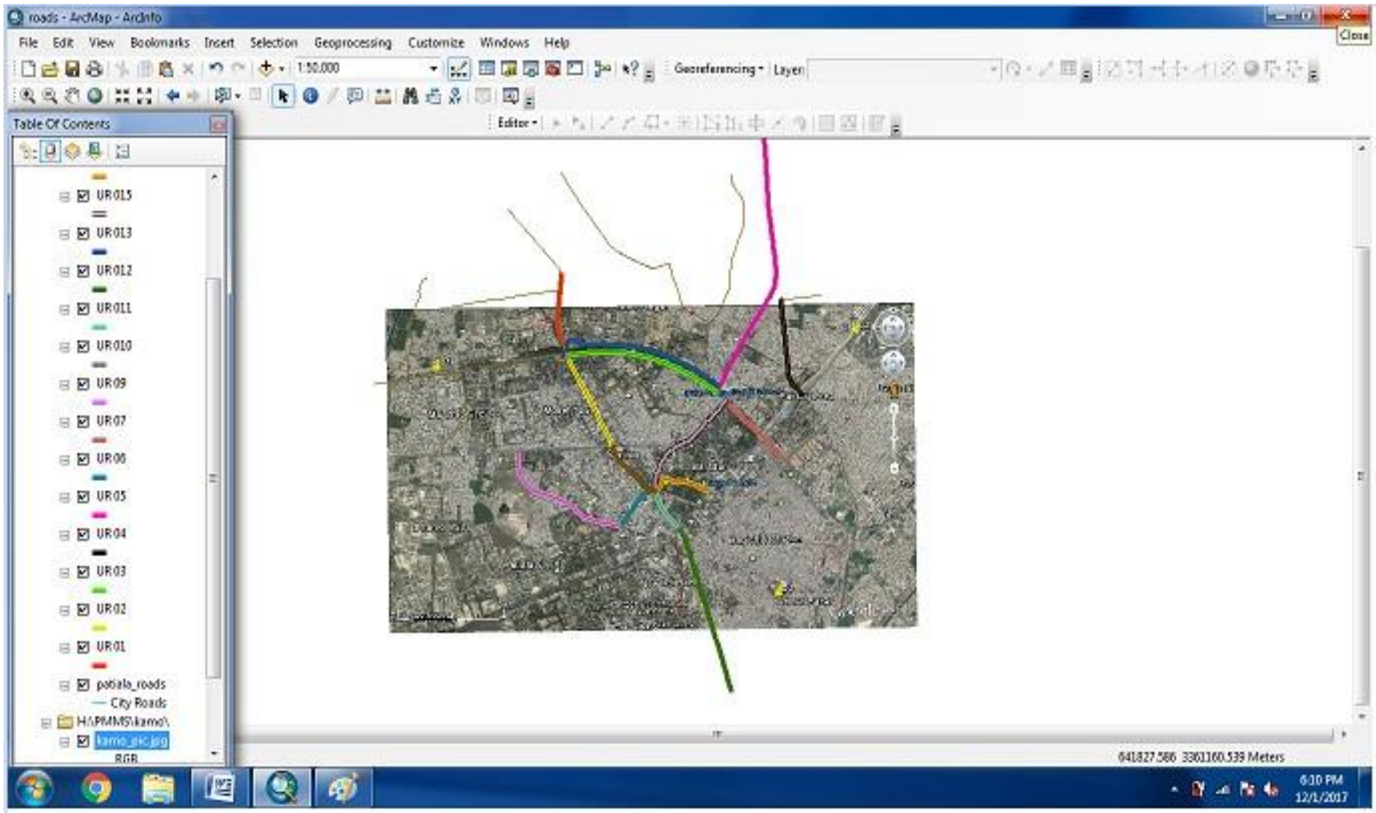


Fig. 5.37: Google Map of Earth Locations of Selected Road Network

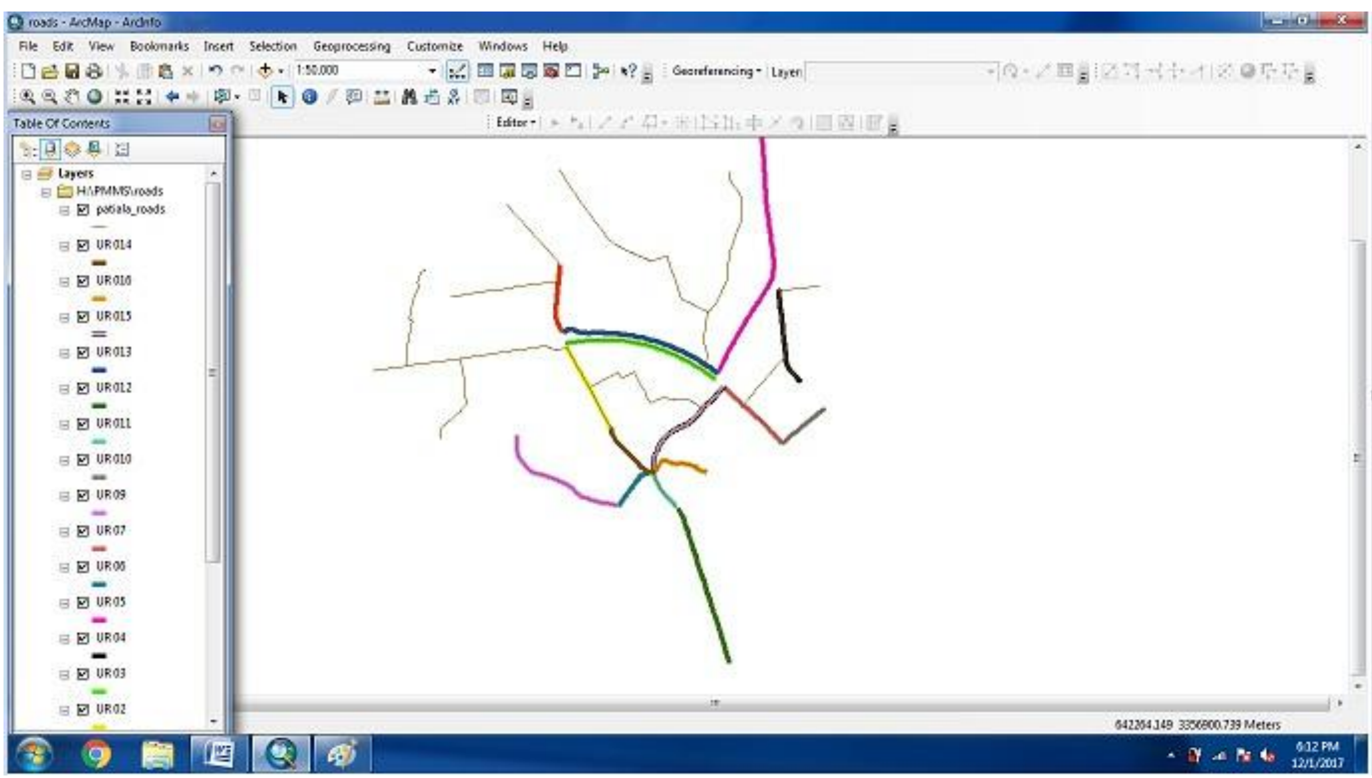


Fig. 5.38: Extraction and Plotting of Selected Urban Road Network of Patiala

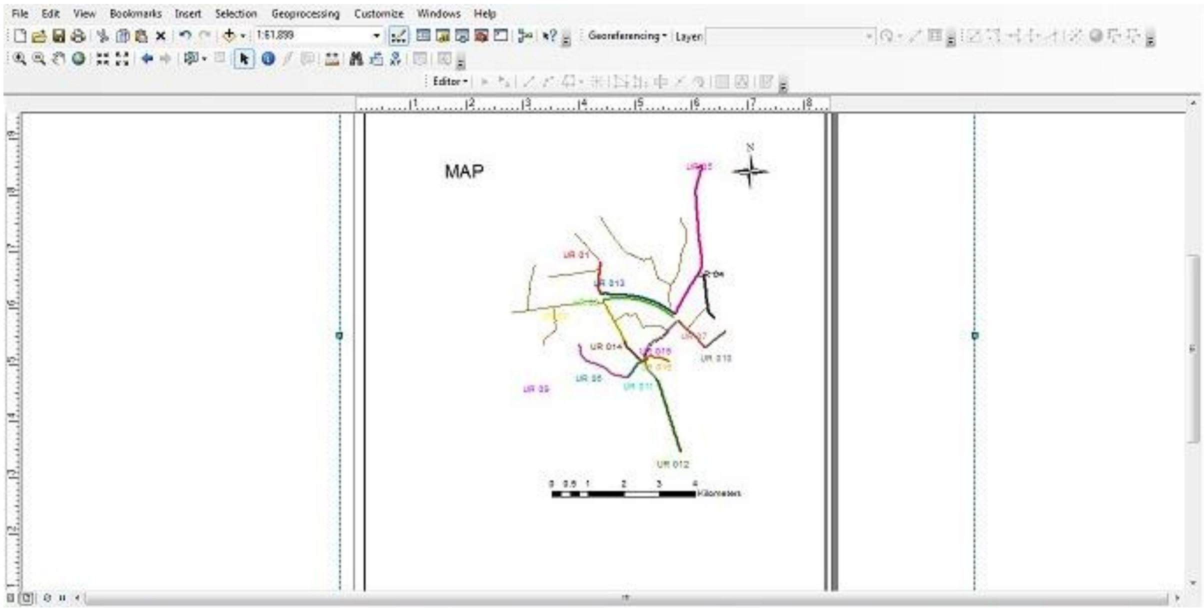
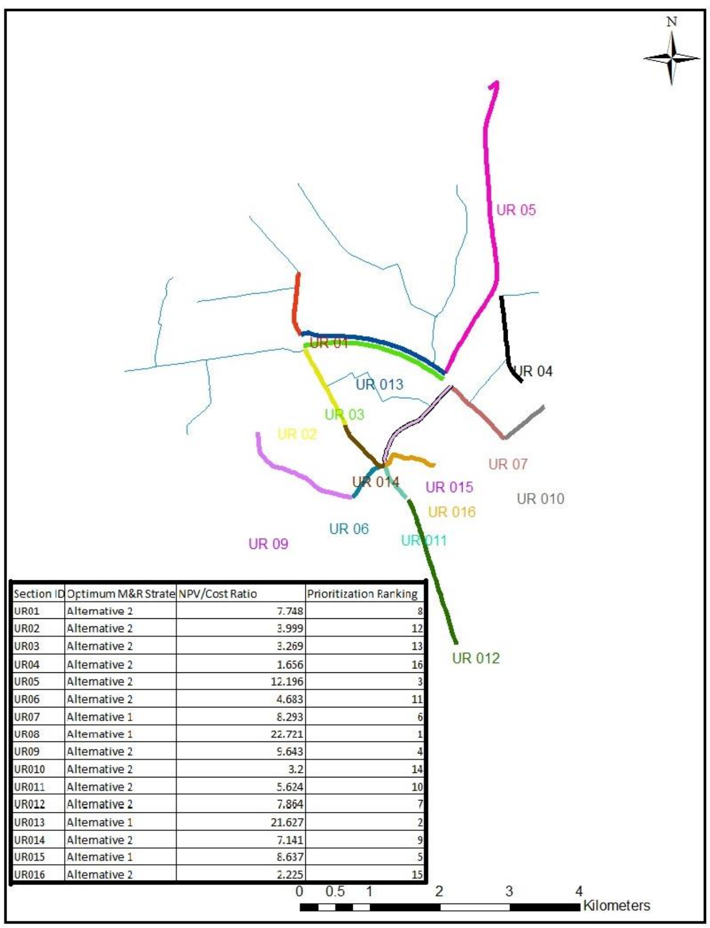
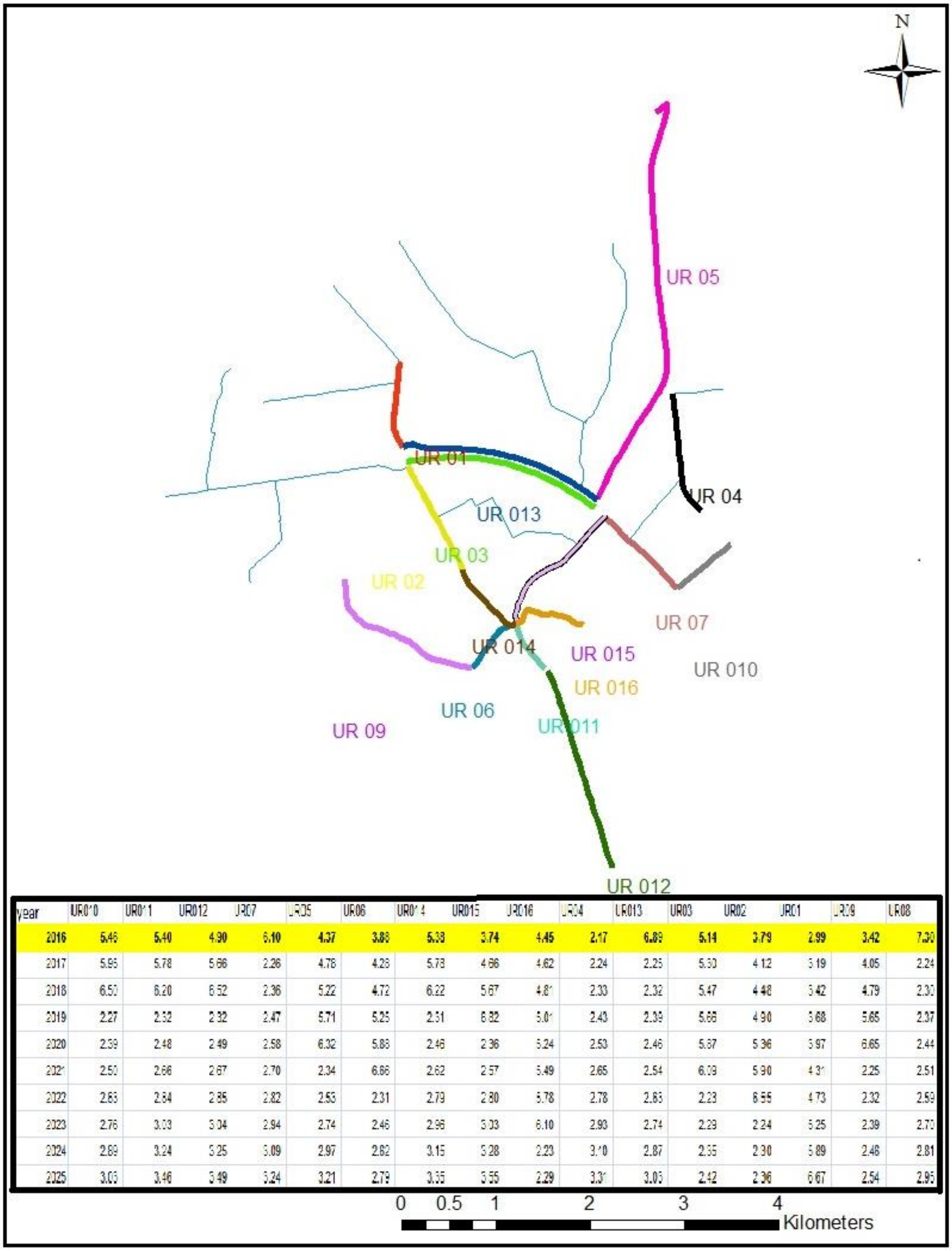


Fig. 5.39: Creating a Map of Selected Urban Road Network



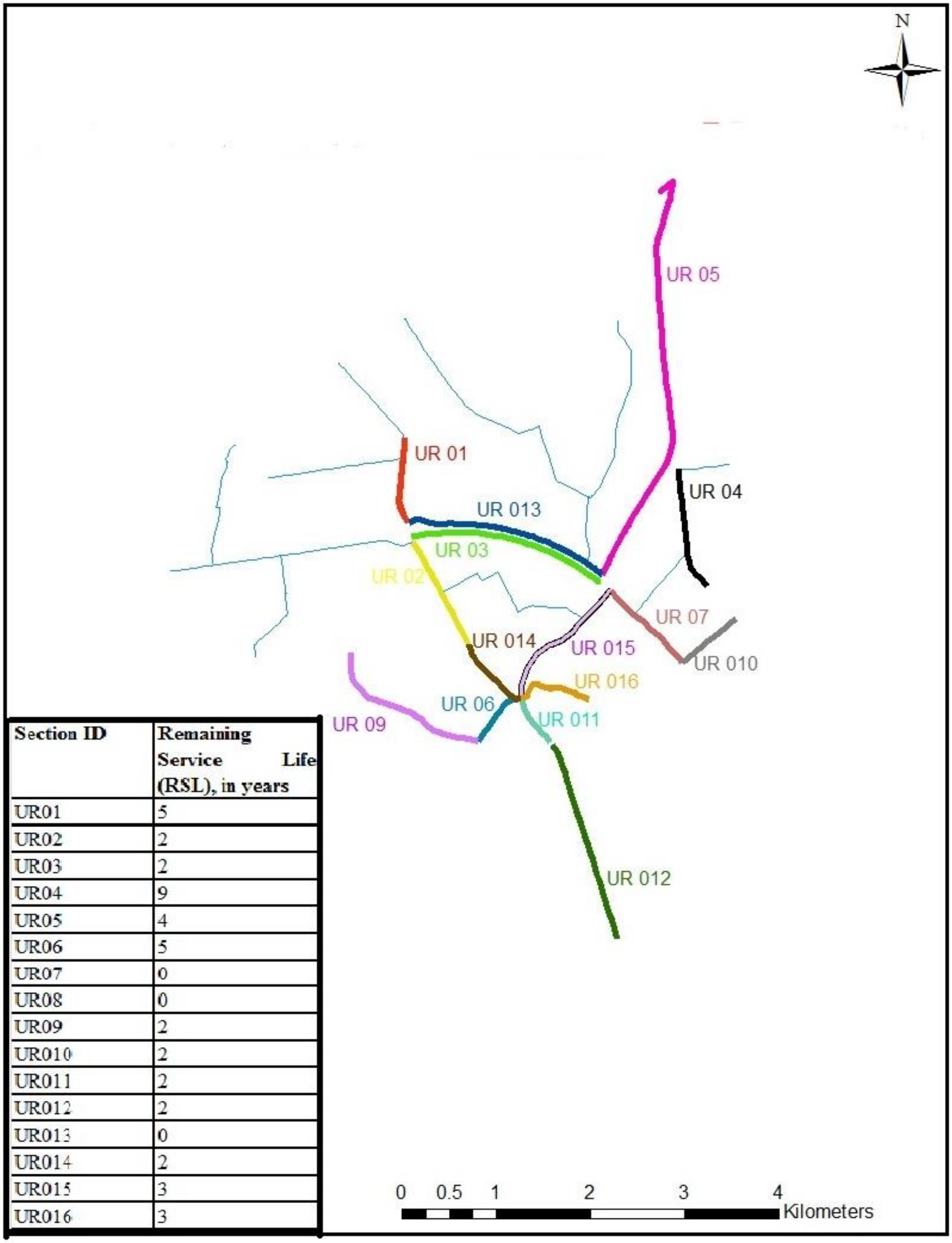
Section ID	Optimum M&R Strate	NPV/Cost Ratio	Prioritization Ranking
UR01	Alternative 2	7.748	8
UR02	Alternative 2	3.999	12
UR03	Alternative 2	3.269	13
UR04	Alternative 2	1.656	16
UR05	Alternative 2	12.196	3
UR06	Alternative 2	4.683	11
UR07	Alternative 1	8.293	6
UR08	Alternative 1	22.721	1
UR09	Alternative 2	9.643	4
UR010	Alternative 2	3.2	14
UR011	Alternative 2	5.624	10
UR012	Alternative 2	7.864	7
UR013	Alternative 1	21.627	2
UR014	Alternative 2	7.141	9
UR015	Alternative 1	8.637	5
UR016	Alternative 2	2.225	15

Fig. 5.40: Prioritization Ranking of Selected Urban Road Network of Patiala with their Optimum M&R Strategy and NPV/Cost Ratio



year	UR010	UR011	UR012	UR07	UR05	UR06	UR014	UR015	UR016	UR04	UR013	UR03	UR02	UR01	UR09	UR08
2016	5.46	5.40	4.90	6.10	4.37	3.88	5.38	3.74	4.45	2.17	6.89	5.14	3.79	2.99	3.42	7.30
2017	5.95	5.78	5.66	2.26	4.78	4.28	5.78	4.66	4.62	2.24	2.25	5.30	4.12	3.19	4.05	2.24
2018	6.50	6.20	6.52	2.36	5.22	4.72	6.22	5.67	4.81	2.33	2.32	5.47	4.48	3.42	4.79	2.30
2019	2.27	2.32	2.32	2.47	5.71	5.25	2.31	6.82	5.01	2.43	2.39	5.66	4.90	3.68	5.65	2.37
2020	2.39	2.48	2.49	2.58	6.32	5.83	2.46	2.36	5.24	2.53	2.46	5.87	5.36	3.97	6.65	2.44
2021	2.50	2.66	2.67	2.70	2.34	6.66	2.62	2.57	5.49	2.65	2.54	6.09	5.90	4.31	2.25	2.51
2022	2.63	2.84	2.85	2.82	2.53	2.31	2.79	2.80	5.78	2.78	2.63	2.23	6.55	4.73	2.32	2.59
2023	2.76	3.03	3.04	2.94	2.74	2.46	2.96	3.03	6.10	2.93	2.74	2.29	2.24	5.25	2.39	2.70
2024	2.89	3.24	3.25	3.09	2.97	2.62	3.15	3.28	2.23	3.10	2.87	2.35	2.30	5.89	2.46	2.81
2025	3.03	3.46	3.49	3.24	3.21	2.79	3.35	3.55	2.29	3.31	3.03	2.42	2.36	6.67	2.54	2.95

Fig.5.41: Progression of Roughness in the Analysis Period for various Road Sections



Section ID	Remaining Service Life (RSL), in years
UR01	5
UR02	2
UR03	2
UR04	9
UR05	4
UR06	5
UR07	0
UR08	0
UR09	2
UR010	2
UR011	2
UR012	2
UR013	0
UR014	2
UR015	3
UR016	3

Fig. 5.42: RSL of Selected Urban Road Network Patiala, Punjab, India

This type of graphical presentation of PMMS through GIS can be very useful for gaining better support from decision makers for adequate and timely fund allocations and effectively identifying, planning and scheduling maintenance works.

5.7 GENERATIONS GENERATED BY GP KERNEL

Some of the Generations from the pool (out of 10000) Produced by GP kernel for Cracking Progression

1	crack = (0.4 + ((log(((sqrt((pre_crack + ((exp(pre_crack) / age) + exp(log((age + pre_crack)))))) + sqrt((sqrt((traffic + exp(pre_crack))) + exp((age / pre_crack))))) / pre_crack)) + traffic) + pre_crack)) CoD: 0.946746 RMS: 0.574903
2	crack = (pre_crack + (exp(traffic) + log(((sqrt(sqrt(((exp(pre_crack) / pre_crack) + (age / traffic)))) + sqrt((age + exp(((traffic + (traffic + sqrt((exp(pre_crack) / pre_crack)))) / age))))) / pre_crack)))) CoD: 0.962136 RMS: 0.468883
3	crack = (pre_crack + (exp(exp(pow(traffic, pre_crack))) + log((((sqrt((exp(((sqrt(exp((((pre_crack + age) + pre_crack) / age))) + pre_crack) / age)) + pre_crack)) + sqrt(age)) / exp(exp(pow(traffic, pre_crack)))) / pre_crack)))) CoD: 0.965762 RMS: 0.474729
4	crack = (pre_crack + (exp(exp(pow(traffic, pre_crack))) + log((((sqrt((exp(((sqrt(exp((((pre_crack + age) + pre_crack) / age))) + pre_crack) / age)) + pre_crack)) + sqrt(age)) / exp(exp(pow(traffic, pre_crack)))) / pre_crack)))) CoD: 0.965762 RMS: 0.474729
5	crack = ((log((((age + ((sqrt((exp(exp((pre_crack / age))) + traffic)) + 3) + pre_crack)) / pre_crack) / ((((MSN + pow(traffic, pre_crack)) + traffic) + pre_crack) + (traffic + MSN)))) + exp(exp(pow(traffic, pre_crack)))) + pre_crack) CoD: 0.975522 RMS: 0.367463
6	crack = ((log((((pre_crack + (pre_crack + sqrt(exp(exp((pre_crack / age)))))) / (pre_crack + MSN)) / pre_crack)) + exp(exp(pow(traffic, pre_crack)))) + pre_crack) CoD: 0.970949 RMS: 0.416509
7	crack = (pre_crack + (log(((((((exp((pre_crack - age)) + pre_crack) + (age + pow(pre_crack, traffic))) + age) + (pre_crack - age)) / pre_crack) / ((pre_crack + (pre_crack + (MSN / pre_crack))) + MSN))) + exp(exp(pow(traffic, pre_crack))))) CoD: 0.972722 RMS: 0.389959
8	crack = (sqrt(((age + ((exp(pre_crack) / ((tanh(sqrt(((MSN / (pre_crack + age)) + pre_crack))) + age) / traffic)) / pre_crack)) / pre_crack)) +

	(sqrt(((pre_crack / exp(pre_crack)) / pre_crack)) + (tanh(traffic) + pre_crack))) CoD: 0.949851 RMS: 0.528406
9	crack = (((((age / pre_crack) / pre_crack) / exp(pre_crack)) + pre_crack) + sqrt((((age + pre_crack) + ((exp(pre_crack) / (age / traffic)) / pre_crack)) / pre_crack))) CoD: 0.953253 RMS: 0.516703
10	crack = (((pre_crack / (exp(pre_crack) + age)) + pre_crack) + sqrt((((((exp(pre_crack) / (age / traffic)) / pre_crack) + age) + ((age + MSN) / pre_crack)) / pre_crack))) CoD: 0.953096 RMS: 0.505334
11	crack = (sqrt(((age + (((pre_crack + (pre_crack + ((exp(pre_crack) / age) / age))) + (pre_crack / (age / traffic))) / pre_crack)) / pre_crack)) + (pre_crack + traffic)) CoD: 0.952635 RMS: 0.510092
12	crack = (sqrt((((((((traffic + pre_crack) / ((pre_crack / pre_crack) / traffic)) / pre_crack) + ((((exp(pre_crack) / ((age / pre_crack) / traffic)) / pre_crack) + age) + pre_crack)) / pre_crack) + (age + pre_crack)) / pre_crack)) + pre_crack) CoD: 0.953695 RMS: 0.529447
13	crack = (pre_crack + sqrt((((((exp(pre_crack) / ((sqrt(traffic) + pre_crack) / traffic)) / age) + sqrt((age + traffic))) + (pow((traffic / traffic), 2) + age)) / pre_crack))) CoD: 0.953555 RMS: 0.510494
14	crack = (sqrt(((((pre_crack + (age + (((MSN + pre_crack) / sqrt(exp(pre_crack))) + (traffic / (pre_crack + MSN))))) / sqrt(MSN)) + (((exp(pre_crack) / (age / traffic)) / pre_crack) + age)) / pre_crack)) + pre_crack) CoD: 0.953655 RMS: 0.524277
15	crack = (pre_crack + sqrt((((MSN + (((pre_crack / pre_crack) + ((exp(pre_crack) / (pre_crack / traffic)) / age)) + traffic)) + age) / pre_crack))) CoD: 0.953283 RMS: 0.503885
16	crack = (sqrt((((((13.2226 + (13.7557 + (pre_crack / exp(sqrt(sqrt(traffic)))))) + (age - traffic)) + ((0.8838 + MSN) + ((exp(pre_crack) / (age / traffic)) / age))) / MSN) / pre_crack)) + pre_crack) CoD: 0.960794 RMS: 0.461473
17	crack = (sqrt(((age + (((((exp(pre_crack) / (age / traffic)) / age) + (MSN +

	13.0969)) / MSN) + ((traffic / (age / (age / pre_crack))) / age))) / pre_crack)) + pre_crack) CoD: 0.959172 RMS: 0.471425
18	crack = (((((MSN + ((pre_crack + pre_crack) / (age / (((MSN / log((pre_crack + traffic))) + sqrt(pre_crack)) / sqrt((pow(MSN, 2) / exp(traffic))))))) / (age / exp(traffic))) + (age / pre_crack)) / sqrt(MSN)) + pre_crack) CoD: 0.96894 RMS: 0.41415
19	crack = (pre_crack + (((((age + MSN) + exp((((MSN / ((MSN + pre_crack) + age)) + pre_crack) / (age / exp(traffic))))) / pre_crack) + (((age + MSN) + exp((pre_crack / ((age + MSN) / exp(traffic))))) / age)) / MSN)) CoD: 0.969015 RMS: 0.42526
20	crack = (((((exp((pre_crack / (age / exp(traffic)))) / age) + ((pre_crack / (pre_crack / (age / exp(traffic)))) / exp(((pre_crack / MSN) / exp(traffic))))) + ((((pre_crack + exp(traffic)) + MSN) + MSN) / pre_crack)) / MSN) + pre_crack) CoD: 0.971014 RMS: 0.400102
21	crack = (pre_crack + (((exp((pre_crack / (age / exp(traffic)))) / age) + ((((exp(traffic) + pre_crack) + (MSN + age)) + exp(exp(traffic))) / pre_crack)) / MSN)) CoD: 0.969601 RMS: 0.424869
22	crack = (((((tanh(pow(tanh(traffic), log(exp(MSN)))) + exp(tanh((MSN - pre_crack)))) / MSN) + ((tanh(log(pre_crack)) / log(MSN)) + exp(pow(traffic, MSN)))) + tanh((MSN - pre_crack))) / log(MSN)) CoD: 0.568497 RMS: 0.517223
23	crack = (tanh(MSN) + (tanh(((pow(pow(traffic, 2), sqrt(traffic)) / (sqrt((MSN / traffic)) - traffic)) / tanh(pow(sqrt((((MSN / pre_crack) / age) / pre_crack)), 2)))) + tanh(((exp(((pre_crack / MSN) / (MSN - traffic))) + log(age)) - pre_crack)))) CoD: 0.750609 RMS: 0.38
24	crack = (((((pre_crack / MSN) + age) / pre_crack) / MSN) + ((pre_crack / age) + (traffic + tanh(tanh((tanh((((age + ((age / traffic) / MSN)) / pre_crack) - pre_crack)) + traffic)))))) CoD: 0.678175 RMS: 0.415864
25	crack = (((age / pre_crack) / MSN) + ((pre_crack / age) + (traffic + ((MSN / ((age / MSN) + (((age / traffic) / traffic) / pre_crack))) + tanh(tanh(tanh(((log(((log(age) + age) / traffic)) + log(pre_crack)) - pre_crack)))))))) CoD: 0.6901

	RMS: 0.427406
26	crack = ((((pow(traffic, pre_crack) * MSN) * ((pow(sqrt(pre_crack), 2.340046) + pow(2.450153, 2.497782)) * 2.489527)) + ((age + ((2.386605 + pow(MSN, sqrt(pre_crack))) + exp((pow(sqrt(pre_crack), 2.569133) / age)))) + age)) / (pow(2.449126, sqrt(pre_crack)) * MSN)) CoD: 0.779223 RMS: 0.344457
27	crack = (((age + (((exp((pow(sqrt(pre_crack), 2.634137) / age)) + age) + age) + pow(sqrt(pre_crack), MSN))) + ((2.626107 * pow(traffic, pre_crack)) * (2.47879 * pow(3.244294, 2.727508)))) / (MSN * pow(2.654665, sqrt(pre_crack)))) CoD: 0.781517 RMS: 0.334823
28	crack = ((((age + (pow(sqrt(pre_crack), MSN) + age)) + (exp((pow(2.657341, sqrt(pre_crack)) / age)) + (age + (2.706174 * pow(traffic, pre_crack))))) + ((pow(2.799489, 3.061511) * 3.131742) * (2.706174 * pow(traffic, pre_crack)))) / (MSN * pow(2.71652, sqrt(pre_crack)))) CoD: 0.781313 RMS: 0.347833
29	crack = ((((pow(2.998311, 3.085923) * age) * pow(traffic, pre_crack)) + (sqrt(pre_crack) + (((((age - traffic) - traffic) + age) + exp((pow(2.635997, sqrt(pre_crack)) / age))) + (pre_crack + (pow(2.464167, sqrt(pre_crack)) * MSN))))) / (MSN * pow(2.901583, sqrt(pre_crack)))) CoD: 0.758257 RMS: 0.355598
30	crack = ((((3.335991 + (pre_crack + (sqrt(2.589815) + MSN))) + ((age + (age + exp((pow(sqrt(pre_crack), 2.6387) / age)))) + pow(sqrt(pre_crack), MSN))) + (pow(traffic, pre_crack) * (pow(3.379081, 2.270327) * (MSN + pre_crack)))) / (pow(2.709692, sqrt(pre_crack)) * MSN)) CoD: 0.772248 RMS: 0.346044
31	crack = ((((pow(2.975663, 2.466263) * ((pre_crack + MSN) + MSN)) * pow(traffic, pre_crack)) + (((2.487862 + MSN) + exp((pow(2.590776, sqrt(pre_crack)) / age))) + (age + ((pow(sqrt(pre_crack), MSN) + age) + sqrt(pre_crack))))) / (MSN * pow(2.684874, sqrt(pre_crack)))) CoD: 0.773971 RMS: 0.349411
32	crack = ((((age + exp((pow(2.593326, sqrt(pre_crack)) / age))) + ((age + sqrt((sqrt(age) + pow(age, 1.3898959)))) + pow(sqrt(pre_crack), MSN))) + ((pow(3.593804, 2.530205) * (MSN + 3.129579)) * pow(traffic, pre_crack))) / (MSN * pow(2.564634, sqrt(pre_crack)))) CoD: 0.784152 RMS: 0.3360
33	crack = (((pow(traffic, pre_crack) * (MSN * pow((traffic + 2.891857), 3.230645))) + (((2.681801 + exp((pow(2.620226, sqrt(pre_crack)) / age))) + (2.821444 + (2.602098 + pow(sqrt(pre_crack), MSN)))) + (age + age))) /

	(pow(2.722376, sqrt(pre_crack)) * MSN)) CoD: 0.786902 RMS: 0.33666
34	crack = (((((2.638096 + exp((pow(2.644367, sqrt(pre_crack)) / age))) + ((age + pow(sqrt(pre_crack), MSN)) + age)) + (2.510937 + (2.851482 + traffic))) + (pow(traffic, pre_crack) * (MSN * pow((2.913766 + traffic), 3.260571)))) / (pow(2.733726, sqrt(pre_crack)) * MSN)) CoD: 0.782257 RMS: 0.337404
35	crack = ((log((((pre_crack + (sqrt(exp(exp((pre_crack / age)))) + ((sqrt(pre_crack) + age) + (sqrt(pow(traffic, age)) + traffic)))) / (pre_crack + sqrt(exp((pre_crack / age))))) / (pre_crack + MSN))) + exp(exp(pow(traffic, pre_crack)))) + pre_crack) CoD: 0.97422 RMS: 0.381755
36	crack = (pre_crack + (exp(exp(pow(traffic, pre_crack))) + log(((((sqrt(exp(exp((exp((pre_crack / age)) / age)))) + ((pre_crack / age) + age)) + pre_crack) / pre_crack) / ((pre_crack + MSN) + exp(pow(pow(traffic, age), traffic))))))) CoD: 0.971926 RMS: 0.400384
37	crack = (pre_crack + (log((((((sqrt((exp(exp((exp((pre_crack / age)) / age))) / (pre_crack / age))) + (traffic + pre_crack)) + pre_crack) / pre_crack) / (MSN + pre_crack))) + exp(exp(pow(traffic, pre_crack))))) CoD: 0.974493 RMS: 0.375142
38	crack = (pre_crack + (exp(exp(pow(traffic, pre_crack))) + log((((((exp(pow(traffic, pre_crack)) + pre_crack) + exp((pre_crack - age))) + (exp(exp(pow(traffic, pre_crack))) / (MSN / age))) / pre_crack) / (pow(pre_crack, traffic) + (MSN + pre_crack)))))) CoD: 0.974205 RMS: 0.377418
39	crack = (pre_crack + (log((((((age + ((traffic + pre_crack) + sqrt(exp(exp((pre_crack / age)))))) + log(age)) / (pre_crack + MSN)) / ((traffic + pre_crack) + exp(pow(traffic, pre_crack))))) + exp(exp(pow(traffic, pre_crack))))) CoD: 0.974828 RMS: 0.377566
40	crack = (pre_crack + (log(((((age + ((traffic + pre_crack) + sqrt(exp(exp((pre_crack / age)))))) / (pre_crack + MSN)) / ((traffic + pre_crack) + (pre_crack / pre_crack)))) + exp(exp(pow(traffic, pre_crack))))) CoD: 0.975156 RMS: 0.367434 crack = ((log((((pre_crack + ((age / MSN) + sqrt(exp(exp((pre_crack / age)))))) / pre_crack) / ((sqrt(sqrt(pre_crack)) + (pre_crack / exp(exp((pre_crack / age))))) + pre_crack))) + exp(exp(pow(traffic, pre_crack)))) + pre_crack)

	CoD: 0.971896 RMS: 0.393307
41	crack = (log(pow(exp(pow(pre_crack, 2)), tanh(pow(pre_crack, 2)))) - (age / MSN)) CoD: 0.935924 RMS: 30.2229
42	crack = (pow(pre_crack, 2) / exp((age / age))) CoD: 0.939705 RMS: 7.87044
43	crack = (pre_crack + sqrt((sqrt(((exp(pre_crack) + exp(pre_crack)) + pow(tanh(((exp(age) * log(traffic)) / tanh(tanh(exp(pre_crack))))), 2))) / sqrt(log(pre_crack))))) CoD: 0.938682 RMS: 3.24042
44	crack = (sqrt(((((exp(pre_crack) / (pow((age / traffic), 2) / pow(pre_crack, 2))) / pow(age, 3)) + ((age + pre_crack) + tanh((log(exp(pow((age - age), 2))) - log(tanh(log(pre_crack))))))) / pre_crack)) + pre_crack) CoD: 0.966524 RMS: 0.485415
45	crack = (sqrt(((((exp(pre_crack) / age) / (pre_crack / traffic)) + (((pre_crack / (age / traffic)) + age) + ((age / traffic) / ((traffic - MSN) + (age + age))))) / pre_crack)) + pre_crack) CoD: 0.9515 RMS: 0.521491
46	crack = (sqrt(((((age + pre_crack) + tanh((log(exp(pow((age - age), 2))) - log((exp(pre_crack) / pre_crack))))) + ((exp(pre_crack) / (pow((age / traffic), 2) / pow(pre_crack, 2))) / pow(age, 3))) / pre_crack)) + pre_crack) CoD: 0.966135 RMS: 0.526781
47	crack = (sqrt((((((pre_crack + (sqrt(MSN) + pre_crack)) + (pre_crack + sqrt(((exp(pre_crack) / (pow(MSN, 2) / traffic)) / (pow(MSN, 2) / (age / traffic)))))) / (pre_crack + traffic)) + (((exp(pre_crack) / (age / traffic)) / pre_crack) + age)) / pre_crack)) + pre_crack) CoD: 0.95521 RMS: 0.501463
48	crack = (((((exp((pre_crack / (age / exp(traffic)))) / age) + (traffic / exp(sqrt((age / traffic))))) + ((((log(pre_crack) + ((log(age) + pre_crack) + MSN)) + MSN) + (age / exp(traffic))) / pre_crack)) / MSN) + pre_crack) CoD: 0.964926 RMS: 0.438448
49	crack = ((pre_crack + (((exp((pre_crack / (age / exp(traffic)))) / age) + (pre_crack / pre_crack)) / MSN)) + ((((MSN + (age + MSN)) / pre_crack) + (exp(traffic) / pre_crack)) / MSN)) CoD: 0.969935 RMS: 0.403243
50	crack = (pre_crack + (exp(exp(pow(traffic, pre_crack))) + log(((exp(((traffic * sqrt(traffic)) / pre_crack)) + (((MSN + pow(traffic, pre_crack)) +

	exp(((pre_crack + exp((pre_crack / age))) / age))) / (MSN + pre_crack))) / pre_crack)))) CoD: 0.965077 RMS: 0.491085

Some of the Generations (out of 10000) Produced by GP kernel for Ravelling Progression

1	Ravel = ((sqrt(pre_ravel) + sqrt(MSN)) + ((traffic + MSN) - sqrt(tanh(traffic)))) CoD: 0.702555 RMS: 2.72556
2	Ravel = ((exp(tanh(((pre_ravel + traffic) * traffic))) + MSN) + tanh(((tanh(log((pre_ravel * traffic))) / sqrt(MSN)) + (tanh(log((pre_ravel * (log(((pre_ravel * traffic) + pre_ravel)) * traffic)))) / log(MSN))))) CoD: 0.809422 RMS: 1.20349
3	Ravel = (exp(tanh((tanh((tanh((tanh((((pre_ravel / MSN) + log((log(pre_ravel) * traffic))) + (MSN - MSN))) + (MSN - MSN))) * ((exp((pre_ravel / traffic)) + MSN) / MSN))) * (pre_ravel / MSN)))) + (exp((pre_ravel / exp(MSN))) + MSN)) CoD: 0.827415 RMS: 0.936256
4	Ravel = ((((((pre_ravel / MSN) / MSN) + log((traffic / pre_ravel))) + ((pre_ravel / MSN) + log((pre_ravel * (log(pre_ravel) + pre_ravel)))))) / MSN) + (exp(tanh(((pre_ravel / MSN) + ((pre_ravel / MSN) + log((log(pre_ravel) * traffic)))))) + MSN)) CoD: 0.817028 RMS: 0.929976
5	Ravel = (((((log(((MSN + (traffic + (log(pre_ravel) + pre_ravel))) / MSN)) + sqrt(pre_ravel)) + sqrt(MSN)) + MSN) / MSN) + (tanh(((log((sqrt(pre_ravel) * traffic)) + (pre_ravel / MSN)) / traffic)) + MSN)) CoD: 0.847191 RMS: 0.865018
6	Ravel = (((((log(sqrt(pre_ravel)) + sqrt(pre_ravel)) + sqrt(MSN)) + MSN) / MSN) + (tanh(((log((sqrt(pre_ravel) * traffic)) + (pre_ravel / MSN)) / traffic)) + MSN)) CoD: 0.84515 RMS: 0.897229
7	Ravel = (((log((MSN * (MSN + MSN))) + (sqrt(pre_ravel) + MSN)) / MSN) + (tanh((tanh(((log((traffic * sqrt(pre_ravel))) + (pre_ravel / MSN)) / traffic)) / traffic)) + MSN)) CoD: 0.845831 RMS: 0.892857
8	Ravel = (((log(exp(MSN)) + (sqrt(pre_ravel) + ((((pre_ravel / MSN) + log((traffic * sqrt(pre_ravel)))) / traffic) / (pre_ravel / MSN)))) / MSN) + MSN) CoD: 0.816299 RMS: 1.32112
9	Ravel = ((tanh((((((log(exp(pre_ravel)) / MSN) + log((sqrt(pre_ravel) * traffic))) /

	traffic) / MSN) / sqrt(traffic))) + MSN) + ((log(MSN) + ((traffic + ((MSN + (pre_ravel + log(traffic))) / log(pre_ravel))) + MSN)) / MSN)) CoD: 0.839684 RMS: 0.875189
10	Ravel = ((((log(MSN) + pre_ravel) / MSN) + (MSN + tanh(sqrt(tanh(MSN))))) + tanh(log((((sqrt(pre_ravel) / log(MSN)) + sqrt(pre_ravel)) * tanh((tanh(traffic) + traffic)))))) CoD: 0.794949 RMS: 0.999143
11	Ravel = (tanh((traffic + tanh(tanh((traffic + (((((traffic + log(traffic)) + (sqrt(traffic) + traffic)) * pre_ravel) + log(((traffic + pre_ravel) * traffic))) + traffic)))))) + (((pre_ravel + MSN) / MSN) + MSN)) CoD: 0.841234 RMS: 0.978057
12	Ravel = ((tanh(tanh((traffic + ((((((traffic + sqrt(traffic)) + (traffic + log(traffic))) * pre_ravel) + (traffic + sqrt(traffic))) * pre_ravel) + sqrt(traffic))))) + (((pre_ravel + MSN) / MSN) + MSN)) + (exp(tanh(sqrt(sqrt(tanh(exp(MSN)))))) / MSN)) CoD: 0.848822 RMS: 0.852464
13	Ravel = ((tanh(tanh(tanh((((traffic + sqrt(traffic)) + (traffic + (traffic + (((traffic + sqrt(traffic)) + (traffic + log(traffic))) * pre_ravel)))) * pre_ravel)))) + (MSN + ((pre_ravel + MSN) / MSN))) + ((tanh(MSN) + sqrt(traffic)) / MSN)) CoD: 0.848423 RMS: 0.868912
14	Ravel = (tanh(tanh(((((traffic + log(traffic)) + (traffic + sqrt(sqrt(traffic)))) * pre_ravel) * (traffic + log(pre_ravel))))) + ((((log(((exp(traffic) + ((pre_ravel + -0.16) / (1.24962866 / traffic))) + MSN)) + MSN) + (pre_ravel + traffic)) / MSN) + MSN)) CoD: 0.844504 RMS: 0.878595
15	Ravel = (((((MSN + (sqrt(traffic) + sqrt(traffic))) + (pre_ravel + tanh((tanh(traffic) / ((traffic + log(traffic)) + (traffic + sqrt(traffic))))))) / MSN) + MSN) + tanh((traffic / ((traffic + log(traffic)) + ((traffic + traffic) + traffic))))) CoD: 0.889487 RMS: 0.715531
16	Ravel = (tanh((traffic / ((traffic + (log(traffic) + traffic)) + (traffic + traffic)))) + ((((pre_ravel + tanh((traffic / ((traffic + log(traffic)) + (sqrt(traffic) + traffic))))) + (tanh((traffic + MSN)) + sqrt(MSN))) / MSN) + MSN)) CoD: 0.890414 RMS: 0.919367
17	Ravel = (tanh((sqrt((tanh(MSN) / MSN)) / ((log(traffic) + traffic) + tanh(MSN)))) + (MSN + ((pre_ravel + (MSN + (tanh((traffic / exp((tanh(MSN) / pre_ravel)))) + ((traffic + traffic) + tanh(traffic))))) / MSN))) CoD: 0.868358 RMS: 0.811116
18	Ravel = (tanh(pre_ravel) + ((MSN + tanh((log(traffic) + (traffic / ((traffic + log(traffic)) + tanh((MSN + log(traffic)))))))) + ((MSN + pre_ravel) / (MSN +

	tanh(traffic))))) CoD: 0.885364 RMS: 0.790908
19	Ravel = ((tanh((traffic / ((tanh(pre_ravel) + log(traffic)) + traffic))) + MSN) + ((((MSN + traffic) + ((traffic + tanh(traffic)) + tanh(((log(MSN) + tanh((pre_ravel + MSN))) / (traffic + traffic))))) + pre_ravel) / MSN)) CoD: 0.866411 RMS: 0.792879
20	Ravel = ((((pre_ravel + traffic) + (log(((MSN + pre_ravel) / MSN)) + tanh(pre_ravel))) / MSN) + ((tanh((traffic + log(sqrt(pre_ravel)))) + MSN) + tanh((tanh(traffic) / ((log(traffic) + traffic) + (traffic / traffic)))))) CoD: 0.867981 RMS: 0.77924
21	Ravel = ((MSN + tanh((((MSN / MSN) / (((MSN + traffic) + pre_ravel) + (traffic / traffic))) / ((traffic + log(traffic)) + (traffic / traffic))))) + ((MSN + (log(traffic) + ((traffic + tanh(MSN)) + pre_ravel))) / MSN)) CoD: 0.845359 RMS: 0.988477
22	Ravel = (traffic + ((MSN + tanh((((((1.3636 - traffic) / traffic) / ((traffic / traffic) + (traffic + log(traffic)))) - ((traffic / traffic) / traffic)) - (traffic + traffic)))) + (((MSN + (traffic / (traffic / traffic))) + pre_ravel) / MSN))) CoD: 0.887345 RMS: 0.943787
23	Ravel = (((pre_ravel + (log(MSN) + MSN)) / MSN) + (MSN + tanh(((tanh(traffic) / tanh(exp(MSN))) / (tanh(MSN) + (traffic + log(traffic))))))) CoD: 0.860389 RMS: 0.820971
24	Ravel = (tanh(pre_ravel) + (tanh(tanh(traffic)) + (tanh((tanh(tanh(tanh(traffic))) / ((MSN / MSN) + (traffic + log(traffic))))) + (MSN + ((pre_ravel + tanh(MSN)) / MSN))))) CoD: 0.868442 RMS: 0.808731
25	Ravel = (tanh(MSN) + (((((pre_ravel + (tanh(MSN) + tanh(traffic))) / (traffic / traffic)) + tanh((traffic / (tanh(MSN) + (traffic + log(traffic)))))) / MSN) + (tanh((tanh(tanh(traffic)) / (tanh(MSN) + (log(traffic) + tanh(traffic))))) + MSN))) CoD: 0.877528 RMS: 0.756862
26	Ravel = (tanh((traffic / ((log(traffic) + traffic) + tanh(((pre_ravel + MSN) / MSN))))) + (MSN + ((pre_ravel + (MSN + (pre_ravel / MSN))) / MSN))) CoD: 0.872904 RMS: 0.766784
27	Ravel = (tanh((tanh(tanh(0.243229598)) / ((log(traffic) + traffic) + (tanh(tanh(tanh((pre_ravel + MSN)))) + traffic)))) + (MSN + (((tanh(tanh(tanh(MSN))) + (MSN + tanh(tanh(MSN)))) + pre_ravel) / MSN))) CoD: 0.873944 RMS: 0.770073
28	Ravel = (tanh((0.241997853 / ((log(traffic) + 0.206807554) + tanh(MSN)))) +

	(((pre_ravel + (tanh(tanh(MSN)) + (traffic + (MSN + tanh(MSN))))) / MSN) + MSN)) CoD: 0.877989 RMS: 0.752286
29	Ravel = (tanh((0.231701791 / tanh(((0.217371061 + log(traffic)) + tanh(MSN))))) + (0.262301147 + (tanh((0.231701791 / ((0.178947255 + pre_ravel) + tanh(MSN)))) + (((((pre_ravel + traffic) + tanh(MSN)) / MSN) + MSN) + tanh(MSN))))) CoD: 0.878538 RMS: 0.773876
30	Ravel = (tanh(((tanh(sqrt(MSN)) / MSN) / ((log(traffic) + traffic) + tanh(MSN)))) + ((tanh(tanh(sqrt(MSN))) + MSN) + (((tanh(MSN) + pre_ravel) + sqrt(MSN)) / MSN))) CoD: 0.878589 RMS: 0.752876
31	Ravel = (tanh((log(sqrt(pre_ravel)) / (tanh((sqrt(traffic) / (tanh(pre_ravel) + (traffic + log(traffic))))) + (traffic + log((sqrt(pre_ravel) / sqrt(MSN))))))) + ((pre_ravel / MSN) + (tanh((MSN / (MSN + traffic))) + MSN))) CoD: 0.894837 RMS: 1.02716
32	Ravel = ((tanh(((traffic / (MSN + traffic)) + (log(traffic) + ((tanh(pre_ravel) / (tanh(pre_ravel) + (log(traffic) + traffic))) + log(traffic))))) + MSN) + ((exp(tanh(log(MSN))) + (pre_ravel + (traffic + MSN))) / MSN)) CoD: 0.891049 RMS: 0.740199
33	Ravel = (((((exp(traffic) + MSN) + pre_ravel) + traffic) / MSN) + (MSN + tanh((tanh(traffic) / (tanh(exp(traffic)) + (log(traffic) + traffic)))))) CoD: 0.871027 RMS: 0.779362
34	Ravel = (((tanh((traffic / ((traffic + log(traffic)) + tanh(MSN)))) + MSN) + tanh((MSN + traffic))) + (((sqrt(traffic) + log(tanh(MSN))) + pre_ravel) / (MSN + tanh(log(tanh(tanh(tanh(((pre_ravel + (traffic + log(MSN))) + tanh(MSN)))))))))) CoD: 0.870501 RMS: 0.77287
35	Ravel = (((tanh(((exp(tanh((pre_ravel - MSN))) + 0.404526) + tanh(pre_ravel))) + MSN) + tanh((traffic / ((traffic + log(traffic)) + tanh(pre_ravel))))) + ((pre_ravel + (MSN + (sqrt(tanh(pre_ravel)) - MSN))) / MSN)) CoD: 0.862794 RMS: 0.812087
36	Ravel = ((((((tanh(MSN) + traffic) + traffic) + tanh(tanh((tanh(traffic) + (pre_ravel + (log(exp(MSN)) + traffic)))))) + pre_ravel) / MSN) + ((tanh(MSN) + MSN) + tanh((0.2664412 / (tanh(MSN) + (traffic + log(traffic))))))) CoD: 0.876921 RMS: 0.75536
37	Ravel = ((((((pre_ravel + traffic) + (tanh(MSN) + traffic)) + (traffic + MSN)) + traffic) / MSN) + (MSN + tanh((0.27428 / (tanh(MSN) + (traffic + log(traffic))))))))

	CoD: 0.873539 RMS: 0.763915
38	Ravel = (exp(tanh((traffic / (tanh(MSN) + (traffic + log(traffic)))))) + ((MSN + tanh((exp(traffic) / (pre_ravel + tanh(((MSN + tanh(MSN)) + MSN)))))) + ((pre_ravel + tanh((0.2508773 / (tanh(MSN) + (MSN + log(traffic)))))) / MSN))) CoD: 0.889205 RMS: 0.758007
39	Ravel = ((MSN + ((pre_ravel + tanh(((traffic + traffic) / tanh((0.2464461 / ((log(traffic) + traffic) + tanh(MSN))))))) / MSN)) + exp(tanh((traffic / (tanh(MSN) + ((exp(traffic) + log(traffic)) + log(traffic))))))) CoD: 0.900849 RMS: 0.701697
40	Ravel = (((pre_ravel + tanh(((pre_ravel + tanh((tanh(tanh(traffic)) + (log(traffic) + traffic)))) / MSN))) / MSN) + (MSN + exp(tanh(((exp(tanh(tanh(sqrt(pre_ravel)))) / pre_ravel) / ((log(traffic) + traffic) + tanh(MSN))))))) CoD: 0.898825 RMS: 0.684431
41	Ravel = (MSN + exp(tanh((((tanh(MSN) * sqrt(MSN)) / (MSN / tanh(sqrt((((tanh(MSN) + pre_ravel) / MSN) + (MSN + exp(traffic))))))) / (tanh(MSN) + (log(traffic) + traffic)))))) CoD: 0.858365 RMS: 1.84439
42	Ravel = ((((MSN + exp(tanh(((pre_ravel / (MSN + (MSN + ((traffic + traffic) / (pre_ravel / pre_ravel))))) / (tanh(MSN) + (log(traffic) + traffic)))))) * MSN) + (pre_ravel + tanh(MSN))) / MSN) CoD: 0.876704 RMS: 0.771851
43	Ravel = (((MSN + pre_ravel) / MSN) + ((MSN + traffic) + tanh(((pre_ravel / MSN) + ((log(traffic) + tanh(((pre_ravel / MSN) + (tanh(MSN) + MSN)))) + traffic))))) CoD: 0.801918 RMS: 1.11385
44	Ravel = ((tanh((tanh((((traffic / (pre_ravel + ((MSN + tanh(pre_ravel)) + pre_ravel))) / MSN) + (traffic / pre_ravel))) + (traffic / ((traffic + log(traffic)) + tanh(log(pre_ravel)))))) + MSN) + ((pre_ravel + (MSN + tanh(pre_ravel))) / MSN)) CoD: 0.866422 RMS: 0.796026
45	Ravel = ((((traffic / (MSN + traffic)) + (log(pre_ravel) + (tanh(MSN) + ((MSN + traffic) + pre_ravel)))) / MSN) + (MSN + tanh(((traffic / ((traffic + log(traffic)) + tanh(log(pre_ravel)))) + log(traffic))))) CoD: 0.882852 RMS: 0.741877
46	Ravel = ((((traffic + MSN) + (pre_ravel + ((traffic + log(MSN)) + tanh(MSN)))) / MSN) + (tanh(((traffic / (tanh(log(pre_ravel)) + (log(traffic) + traffic))) + log(traffic))) + MSN)) CoD: 0.884772

	RMS: 0.751575
47	Ravel = (tanh((traffic / ((traffic + log(traffic)) + tanh((log(sqrt(MSN)) + MSN))))) + ((((pre_ravel + (tanh((log(MSN) + MSN)) + (MSN + (pre_ravel / MSN)))) + log(traffic)) / MSN) + MSN)) CoD: 0.870631 RMS: 0.772855
48	Ravel = (((((MSN + pre_ravel) + sqrt((tanh(pre_ravel) / traffic))) / MSN) + MSN) + tanh((MSN / ((traffic + log(traffic)) + tanh(MSN))))) CoD: 0.850864 RMS: 0.87235
49	Ravel = (tanh((traffic / (tanh(((MSN + tanh((pre_ravel + MSN))) + (traffic + traffic))) + (traffic + log(traffic))))) + (((pre_ravel + (MSN + tanh(((MSN + ((MSN + MSN) + tanh((MSN + MSN)))) / pre_ravel)))) / MSN) + MSN)) CoD: 0.863217 RMS: 0.81395
50	Ravel = (((((MSN + ((pre_ravel + (pre_ravel * traffic)) + (MSN + (exp(sqrt(pre_ravel)) + exp(sqrt(pre_ravel)))))) / (pre_ravel + traffic)) + MSN) / MSN) + (MSN + tanh((pre_ravel * (pre_ravel * (((pre_ravel * traffic) * pre_ravel) - MSN)))))) CoD: 0.860624 RMS: 0.813423

Some of the Generations (out of 10000) Produced by GP kernel for Pothole Progression

1	Pot = ((((sqrt(sqrt(Thick_bitu)) + pre_POT) / sqrt(sqrt(CQ))) - sqrt(sqrt(pre_POT))) - traffic) CoD: 0.989349 RMS: 0.205179
2	Pot = (((sqrt(sqrt((tanh(sqrt(pow(traffic, 2))) / (sqrt(pow(sqrt(((sqrt(sqrt(traffic)) / sqrt(sqrt(CQ))) + pre_POT)), 2)) / sqrt(sqrt(pre_POT)))))) + (pre_POT + sqrt(sqrt(CQ)))) / sqrt(sqrt(CQ))) - CQ) CoD: 0.990878 RMS: 0.174614
3	Pot = ((((sqrt(sqrt(sqrt(Thick_bitu))) + (sqrt(tanh((sqrt(sqrt(sqrt(sqrt(sqrt(CQ))))) / sqrt(sqrt(CQ))))) + pre_POT)) / sqrt(sqrt(sqrt(CQ)))) - CQ) - CQ) CoD: 0.998939 RMS: 0.0769674
4	Pot = ((((sqrt(sqrt(CQ)) + ((tanh((sqrt(sqrt(sqrt(sqrt(sqrt(sqrt(sqrt(sqrt(CQ)))))))) / sqrt(sqrt(CQ)))) + tanh(sqrt(sqrt(sqrt(sqrt(((CQ + pre_POT) / CQ))))))) + pre_POT)) / sqrt(sqrt(sqrt(CQ)))) - CQ) - CQ) CoD: 0.997729 RMS: 0.0984657
5	Pot = ((((pow((CQ / CQ), sqrt(CA)) + (pre_POT + (tanh(tanh(sqrt(tanh(tanh((sqrt(sqrt(CQ)) + sqrt(CQ))))))) + tanh(sqrt(sqrt(sqrt(RA))))))) / sqrt(sqrt(sqrt(CQ)))) - CQ) - CQ)

	CoD: 0.999108 RMS: 0.0765209
6	Pot = ((((sqrt(tanh(((sqrt(sqrt(sqrt(CQ))) + pow(CA, 2)) / pow(CQ, traffic)))) + (pre_POT + (tanh(tanh(sqrt(tanh(tanh((sqrt(sqrt(CQ)) + sqrt(CQ))))))) + tanh(sqrt(sqrt(sqrt(RA))))))) / sqrt(sqrt(sqrt(CQ)))) - CQ) - CQ) CoD: 0.999108 RMS: 0.0765326
7	Pot = (((((2.98 + pre_POT) + ((1.644 + 1.399) / (CQ + (tanh(1.715) + ((sqrt(CQ) + (CQ + (tanh(CQ) + ((sqrt(CQ) + CQ) + CQ)))) + CQ))))) - CQ) - CQ) - CQ) CoD: 0.999773 RMS: 0.0374692
8	Pot = ((pre_POT + 4.615) - (((tanh((tanh(CQ) + CQ)) + tanh(CQ)) + pow(tanh(((tanh(tanh(CQ)) + CQ) + sqrt(tanh(tanh(tanh(4.973)))))), 2)) + (tanh(sqrt(pow((tanh(0.27) * CQ), 2))) + CQ))) CoD: 0.99568 RMS: 0.137872
9	Pot = ((4.63 + pre_POT) - (((tanh(tanh(tanh(tanh((CQ + tanh(CQ)))))) + (CQ + (tanh(tanh(tanh(tanh(tanh(tanh(tanh(CQ))))))) + tanh(CQ)))) + CQ) + tanh(tanh(tanh(tanh(tanh(tanh(CQ)))))))) CoD: 0.999919 RMS: 0.0226102
10	Pot = ((4.892 + pre_POT) - ((CQ + (tanh(CQ) + tanh(CQ))) + (CQ + tanh((sqrt(CQ) + (tanh(CQ) + tanh(CQ))))))) CoD: 0.999844 RMS: 0.0263898
11	Pot = ((4.692 + pre_POT) - (tanh((tanh(tanh(((Thick_bitu - Thick_bitu) * (pre_POT - sqrt((4.505 + pre_POT)))))) + CQ)) + (CQ + ((tanh(tanh((((tanh(CQ) + pow(CQ, 2)) + tanh(tanh(CQ))) + (tanh(CQ) + pow(CQ, 2))))) + tanh(CQ)) + CQ)))) CoD: 0.999959 RMS: 0.0149548
12	Pot = sqrt(pow((traffic + pre_POT), (MSN - pre_POT))) CoD: 0.510638 RMS: 3.96811
13	Pot = (exp((2.972 / (exp(CQ) + pow(pow(((CQ + CQ) + pow(((CQ + CQ) + pow(CQ, (exp(pre_POT) + pow(sqrt(sqrt(MSN)), CQ)))), CQ)), CQ), pow((sqrt(CQ) + CQ), ((exp(CQ) + 3.531) + CQ)))))) + pre_POT) CoD: 0.99965 RMS: 0.034322
14	Pot = (exp((3.024 / (pow(pow(((CQ + pow(CQ, CQ)) + pre_POT), CQ), CQ) + pow(pow(exp((0.12 + (pow(CQ, CQ) + pow((exp(((CQ + CQ) + CQ)) + CQ), CQ))))), pow(CQ, CQ)), CQ)))) + pre_POT) CoD: 0.999878 RMS: 0.0238202
15	Pot = (pre_POT + exp((2.981 / (pow(pow(exp(CQ), pow(exp(CQ), (exp(CQ) + CQ))), CQ) + (pow((pow(3.333, CQ) + (CQ + CQ)), CQ) + CQ))))) CoD: 0.999989 RMS: 0.0104998

16	Pot = (exp((3.125 / (exp(CQ) + pow((CQ + ((pow(pow((pow((CQ + (2.633 + CQ)), exp((CQ + (CQ + CQ)))) + 2.518), CQ), CQ) + exp(CQ)) + exp(CQ))), CQ)))) + pre_POT) CoD: 0.99996 RMS: 0.0144579
17	Pot = (pre_POT + exp((3.046 / (pow((pow(CQ, 3.448) + pow((CQ + exp(pow(pow(((3.046 + pre_POT) + CQ), CQ), CQ))), CQ)), (CQ + CQ)) + exp(CQ))))) CoD: 0.999297 RMS: 0.0917251
18	Pot = (pre_POT + exp((2.839 / (pow(pow(exp(CQ), ((CQ + CQ) / sqrt(CQ))), CQ) + pow((pow(exp((CQ + CQ)), (pow(exp(CQ), (CQ + CQ)) + 0.21)) + (CQ + CQ)), CQ))))) CoD: 0.999925 RMS: 0.0189626
19	Pot = (pre_POT + exp((2.672 / (pow(CQ, CQ) + pow((CQ + exp(pow(exp(exp(CQ)), CQ))), CQ))))) CoD: 0.999867 RMS: 0.0232332
20	Pot = (pre_POT + exp((3.17 / (pow(3.028, CQ) + pow((log(exp(traffic)) + exp(pow(pow((CQ + (exp(pow((exp(pow(3.025, CQ)) + CQ), CQ)) + exp(CQ))), CQ), CQ))), CQ))))) CoD: 0.999669 RMS: 0.0475069
21	Pot = (exp((2.884 / (pow(exp(pow(exp(pow(exp(pow((pow(CQ, traffic) + CQ), CQ)), CQ)), CQ)), CQ) + pow(pow(CQ, CQ), CQ)))) + pre_POT) CoD: 0.999943 RMS: 0.0191487
22	Pot = (exp((2.997 / (exp(CQ) + pow(exp(pow((pow(pow((CQ + 2.684), pow((2.668 + CQ), CQ)), CQ) + pow(pow(exp(sqrt((pow(2.536, CQ) + CQ))), CQ), CQ)), CQ)), CQ)))) + pre_POT) CoD: 0.9997 RMS: 0.0426332
23	Pot = (pre_POT + exp((3.114 / (pow(pow(exp(CQ), exp(CQ)), pow(pow(pow(exp(CQ), CQ), pow(pow(exp(CQ), CQ), pow(exp((CQ + CQ)), CQ))), CQ)) + pow(2.93, CQ))))) CoD: 0.999964 RMS: 0.0167933
24	Pot = log((pow((((log((pow((log((pow((((((pre_POT + log(pre_POT)) / CQ) / pre_POT) + pre_POT) + pre_POT), 1) / CQ)) + (pre_POT + pow(pre_POT, 3))), 1) / CQ)) / CQ) / pre_POT) + ((pre_POT / pre_POT) + pow(pre_POT, 3))), 1) / CQ)) CoD: 0.995652 RMS: 0.156768
25	Pot = log((pow((pow(pre_POT, 3) + (log((pow(log(((pow(((pre_POT + MSN) + log(MSN)), 1) / CQ) + (pow(pre_POT, 3) + age))), 1) / CQ)) + log((pow((pow(CQ, 3) + MSN), 1) / CQ)))), 1) / CQ)) CoD: 0.990623

	RMS: 0.183132
26	Pot = log((pow(((pre_POT + ((pow(pre_POT, 3) + pre_POT) / pow(pre_POT, 3))) + pow(pre_POT, 3)), 1) / CQ)) CoD: 0.981707 RMS: 0.274134
27	Pot = log((pow(((pow(((pre_POT / pre_POT) + ((log((pow((pow(pre_POT, 3) + pow(pre_POT, 3)), 1) / CQ)) / (pow(pre_POT, 3) + pre_POT)) / CQ)), 1) / CQ) + pow(pre_POT, 3)), 1) / CQ)) CoD: 0.991489 RMS: 0.192553
28	Pot = log((pow((pow(pre_POT, 3) + ((-0.637 + ((((CQ / (-0.634 / (-0.646 / CQ))) / pow(pre_POT, 3)) + pre_POT) / tanh(CQ))) / pre_POT)), 1) / CQ)) CoD: 0.997447 RMS: 0.122992
29	Pot = log((pow((((pre_POT + (pow(((pre_POT / (pow(CQ, 2) + tanh((tanh(exp(log((age + (pre_POT + tanh(pow(pre_POT, 3))))))) + pow(CA, 0.130203158))))) + pre_POT), 2) / pre_POT)) / pow(pre_POT, 3)) + pow(pre_POT, 3)), 2) / CQ)) CoD: 0.989878 RMS: 0.20781
30	Pot = log((pow(((pow(pre_POT, 3) + ((tanh((CQ / pre_POT)) + (pre_POT / pre_POT)) / CQ)) + tanh(exp(CQ))), 1) / CQ)) CoD: 0.994797 RMS: 0.192377
31	Pot = log((pow(((tanh(pow(CQ, 1)) / pre_POT) + (((((tanh((tanh(age) / pow(pow(pre_POT, 3), 2))) / pow(pre_POT, 1)) + tanh(age)) / CQ) / pow(pre_POT, 3)) + pow(pre_POT, 3))), 1) / pow(CQ, 1))) CoD: 0.998088 RMS: 0.0909774
32	Pot = log((((log((((((exp(pow(CQ, 2)) + tanh(tanh(pow(pre_POT, 2)))) + (pre_POT + CQ)) / pow(CQ, 3)) + pow(pow(pow(tanh(pre_POT), (CQ / pre_POT)), 3), 1)) / CQ)) + ((exp(CQ) / pre_POT) + CQ)) + pow(pow(pre_POT, 3), 1)) / CQ)) CoD: 0.990719 RMS: 0.177333
33	Pot = log(((pre_POT + ((pow(pow(pre_POT, 3), 1) + log(RA)) + (MSN / pow(pre_POT, 3)))) / CQ)) CoD: 0.990181 RMS: 0.182325
34	Pot = log(((pow((pow(pre_POT, 3) + pre_POT), 1) + (((log(((pow(pow(pow(pre_POT, 3), 3), 1) + pow(pow(log((((tanh((pre_POT + pre_POT)) + pow(tanh(pre_POT), 2)) + pre_POT) / CQ)), 1), 1)) / CQ)) + pre_POT) + pre_POT) / pre_POT)) / CQ)) CoD: 0.98151 RMS: 0.372013
35	Pot = log(((pow(pow(pre_POT, 2), 2) + (((CQ + (CQ + pow(pow(pre_POT, 2), 2))) + ((log(((pow(pre_POT, 2) + MSN) / CQ)) / CQ) / CQ)) / pow(pow(pre_POT, 2), 2))) / CQ))

	CoD: 0.992794 RMS: 0.158445
36	Pot = log((((((pre_POT + (((exp(sqrt(sqrt(pow(sqrt(tanh((traffic + CQ))), 2)))) / pre_POT) / age) + (pre_POT + (pre_POT + pre_POT)))) / pow(pre_POT, CQ)) / (pre_POT * CQ)) + pow(pow(pre_POT, 2), 2)) / CQ)) CoD: 0.997122 RMS: 0.10516
37	Pot = log(((((log((((pow(pre_POT, traffic) + CQ) + pow(((pow(pre_POT, 2) + pre_POT) / (pow(CQ, 2) + pow(pre_POT, 2))), 2)) / CQ)) / CQ) + ((MSN / pre_POT) / pre_POT)) + pow(pow(pre_POT, 2), 2)) / CQ)) CoD: 0.997329 RMS: 0.128848
38	Pot = log(((pow(pow(pre_POT, 2), 3) + (((((log(pre_POT) / (pre_POT / sqrt(pow(CQ, 1)))) / pre_POT) + ((CQ / pre_POT) + MSN)) + MSN) / pow(pre_POT, 2))) / CQ)) CoD: 0.988134 RMS: 0.21322
39	Pot = log(((((MSN / (pow(pow(CQ, 1), 3) + pow(pre_POT, 3))) + pow(((((MSN / (pow(pow(CQ, 1), 3) + pow(pre_POT, 3))) + pow(pow(pre_POT, 1), 3)) + MSN) / CQ), 3)) + MSN) / CQ)) CoD: 0.997137 RMS: 9.34196
40	Pot = log(((pow(pow(pre_POT, 1), 3) + ((Thick_bitu + sqrt((CQ + CQ))) / (age + pow(pow(pre_POT, 2), 3)))) / pow(CQ, 1))) CoD: 0.996864 RMS: 0.105411
41	Pot = log((((sqrt(pre_POT) + CQ) + (log(((pre_POT / pre_POT) + pow(((pre_POT + pow(exp(log(pow(pre_POT, 1))), 1)) / pow(pow(pow(CQ, 1), 3), 1)), 1))) + pow(pow(pre_POT, 1), 3))) / pow(CQ, 1))) CoD: 0.995424 RMS: 0.129031
42	Pot = log((((((((((pre_POT + pre_POT) + MSN) + CQ) / tanh(CQ)) / (pre_POT + pre_POT)) + pow(pow(pre_POT, 1), 3)) + (exp((log(RA) - exp(pre_POT))) / tanh(pre_POT))) / CQ)) CoD: 0.994404 RMS: 0.135146
43	Pot = log(((log(((tanh(((pow(pow(pre_POT, 1), pow(pow(pre_POT, 1), 3)) / pre_POT) / pow(CQ, 1))) + (MSN + pow(pow(CQ, 1), 3))) / pow(CQ, 1))) + (MSN + pow(pow(pre_POT, 1), 3))) / pow(CQ, 1))) CoD: 0.995271 RMS: 0.132186
44	Pot = log((((MSN / (CQ + (log(pow(pre_POT, 1)) + CQ))) + (((MSN / (pow(pre_POT, 3) / pre_POT)) + pow(pow(pre_POT, 1), 3)) + pow(CQ, 1))) / pow(CQ, 1))) CoD: 0.996545 RMS: 0.127079
45	Pot = (sqrt((log(tanh(sqrt((tanh(-1.) + pow(CQ, -1.))))) + pow(CQ, -0.94))) +

	(pre_POT + tanh(sqrt((-1.3 + pow(CQ, -1.2)))))) CoD: 0.99973 RMS: 0.0768364
46	Pot = ((pre_POT + (pow(tanh((exp(MSN) - exp(CQ))), 2) / pow(((CQ * exp(tanh(MSN))) + CQ), CQ))) + sqrt((pow(CQ, -0.99) + -0.83))) CoD: 0.995562 RMS: 0.123236
47	Pot = ((tanh(tanh(((sqrt(sqrt((pow(CQ, -1.) + -1.2))) + tanh((sqrt(pow(CQ, -1.)) + tanh(-1.2)))) + -1.2))) + pre_POT) + sqrt((pow(CQ, CQ) + pow(CQ, -0.97)))) CoD: 0.999368 RMS: 0.0651979
48	Pot = ((pre_POT + tanh(((sqrt(pow(CQ, -1.1)) + tanh(pow(tanh(pre_POT), 2))) / (pow(sqrt(pre_POT), -1.1) / pow(CQ, -1.1))))) + sqrt((pow(CQ, -1.1) + -1.3))) CoD: 0.995794 RMS: 0.134205
49	Pot = (((pow(CQ, sqrt(sqrt(sqrt((pow(CQ, -1.) + exp((pre_POT * (pre_POT * -1.2)))))))) + pre_POT) + tanh(tanh((tanh((pow(CQ, -0.92) + -1.1)) * tanh(pow((traffic + CA), sqrt(pow(MSN, 2)))))))) + sqrt((-1.2 + pow(CQ, -1.)))) CoD: 0.998698 RMS: 0.0872316
50	Pot = ((pre_POT + tanh(pow(pow(((-0.98 + pow(CQ, -1.2)) + (pow(CQ, -1.) + -1.)), CQ), pow(CQ, -1.)))) + sqrt((-0.98 + pow(CQ, -1.)))) CoD: 0.999976 RMS: 0.0103695

Some of the Generations (out of 10000) produced by GP kernel for Rutting Progression

1	rut = (pre_rut + (drain_fac + log(sqrt((MSN * tanh(exp((0.1573 - log((pre_rut + (drain_fac + log(sqrt((((drain_fac + log(((pre_rut + (tanh(MSN) + drain_fac)) + log(drain_fac)))) + drain_fac))))))))))))))) CoD: 0.918048 RMS: 0.469667
2	rut = (pre_rut + (drain_fac + tanh((sqrt(log(pre_rut)) - log(pre_rut))))) CoD: 0.919551 RMS: 0.442297
3	rut = (pre_rut + (drain_fac + tanh(tanh(tanh((((exp((drain_fac - exp((sqrt(MSN) - traffic)))) / (MSN - pre_crack)) + tanh(pre_crack)) - (exp((MSN - MSN)) + traffic))))))) CoD: 0.94556 RMS: 0.422787
4	rut = ((drain_fac + tanh((((exp(((pre_rut - sqrt(MSN)) - exp(((tanh(exp(MSN)) / drain_fac) + tanh(exp(pre_crack)))))) / (MSN - pre_crack)) + tanh(sqrt(exp(log(MSN))))) - tanh(age)))) + pre_rut) CoD: 0.962512 RMS: 0.331706

5	rut = (pre_rut + (drain_fac + tanh((exp((log(MSN) - exp(((drain_fac / drain_fac) + tanh(exp((((tanh(exp((tanh((pre_rut - pre_rut)) + tanh(drain_fac)))) / drain_fac) / ((tanh(pre_rut) / (pre_rut / tanh(tanh(drain_fac)))) + drain_fac)) - pre_rut))))))) / (MSN - pre_rut))))) CoD: 0.955571 RMS: 0.426217
6	rut = (pre_rut + (drain_fac + tanh((exp((tanh(((traffic * pre_rut) / exp(drain_fac))) - exp(((MSN - tanh((pre_crack / age))) / pre_rut)))) / (MSN - (drain_fac + tanh(drain_fac))))))) CoD: 0.986133 RMS: 0.186362
7	rut = (pre_rut + (tanh((exp((tanh(tanh(tanh((tanh(tanh(tanh((tanh(drain_fac) - (exp(tanh(exp(sqrt(MSN)))) + drain_fac))))) / sqrt(sqrt(MSN)))))) - tanh((drain_fac + drain_fac)))) / (MSN - (drain_fac + (MSN / MSN))))) + drain_fac)) CoD: 0.966142 RMS: 0.323454
8	rut = ((drain_fac + tanh((pre_rut / (((tanh((MSN - pre_rut)) / (MSN + drain_fac)) - (MSN / (pre_rut / ((sqrt(((drain_fac + exp(log(age))) + pre_rut)) / traffic) / tanh((drain_fac + exp(log(MSN)))))))) - (MSN / traffic))))) + pre_rut) CoD: 0.925947 RMS: 0.426027
9	rut = ((drain_fac + tanh(((log(exp(traffic)) / (traffic - (tanh(pre_crack) / traffic))) / (MSN / log(pre_rut))))) + pre_rut) CoD: 0.922852 RMS: 0.441795
10	rut = (((traffic / ((traffic / (log(MSN) + pre_rut)) - ((MSN + (sqrt((sqrt(tanh((drain_fac + (pre_rut + tanh(((sqrt((sqrt(pre_crack) + tanh(0.316634))) - (pre_rut / MSN)) / tanh(pre_rut))))))) + tanh(0.318783))) + pre_rut)) / pre_rut))) + drain_fac) + pre_rut) CoD: 0.924968 RMS: 0.449184
11	rut = (pre_rut + (drain_fac + ((drain_fac + tanh((((pre_rut + pre_rut) + pre_rut) / (pre_crack + (drain_fac - (exp(MSN) + tanh(age))))))) + pre_rut))) CoD: 0.938715 RMS: 5.28273
12	rut = ((drain_fac + tanh(tanh((drain_fac / (drain_fac + (pre_rut - (exp(MSN) + traffic))))))) + pre_rut) CoD: 0.935185 RMS: 0.481524
13	rut = (pre_rut + (drain_fac + tanh(tanh((pre_rut / ((pre_crack / (tanh(pre_crack) + drain_fac)) + ((pre_rut / ((pre_crack / (tanh(pre_rut) + drain_fac)) + ((pre_rut / tanh(pre_rut)) - exp(MSN)))) - exp(MSN)))))))) CoD: 0.913417 RMS: 0.471494
14	rut = (pre_rut + (drain_fac + tanh((log(MSN) / ((((exp(MSN) - exp(pre_rut)) / tanh((drain_fac / exp(tanh(drain_fac))))) - traffic) + (log(pre_rut) +

	pre_rut)))))) CoD: 0.955126 RMS: 0.417112
15	rut = (pre_rut + (drain_fac + tanh(((log(exp(pre_crack)) - (-0.322995543 + MSN)) / (((drain_fac + pre_rut) - exp(drain_fac)) + ((pre_rut / log(exp(pre_rut))) - exp(MSN))))))) CoD: 0.916336 RMS: 0.452906
16	rut = (pre_rut + (drain_fac + tanh(tanh((exp(log(drain_fac)) / (pre_rut + ((drain_fac - exp(MSN)) + MSN))))))) CoD: 0.932754 RMS: 0.462974
17	rut = ((tanh(((pre_rut - (tanh((pre_rut + (MSN + MSN))) + tanh(log(pre_rut)))) / (MSN + (((pre_rut + MSN) - MSN) - exp(MSN))))) + drain_fac) + pre_rut) CoD: 0.928027 RMS: 0.449316
18	rut = ((tanh((tanh(pre_rut) / ((pre_rut + ((pre_rut / tanh((tanh((pre_rut / ((tanh((pre_rut / (drain_fac - exp(MSN)))) + drain_fac) + pre_rut))) + drain_fac))) / ((((MSN * -0.752739906) + MSN) + pre_rut) / MSN))) - exp(MSN)))) + drain_fac) + pre_rut) CoD: 0.93582 RMS: 0.505687
19	rut = (pre_rut + (tanh((exp(((((pre_rut / (tanh(traffic) + drain_fac)) - tanh(((pre_rut / exp((traffic - pre_rut))) * MSN))) + (log(traffic) + drain_fac)) * traffic)) / (tanh(pre_rut) - exp(MSN)))) + drain_fac)) CoD: 0.924754 RMS: 0.432148
20	rut = (pre_rut + (tanh((pre_rut / (((pre_rut - pre_rut) / drain_fac) - age))) + drain_fac)) CoD: 0.919304 RMS: 0.553608
21	rut = ((tanh((pre_rut / (((((sqrt(sqrt(pre_rut)) / drain_fac) - exp(MSN)) + drain_fac) - MSN) - pre_rut))) + drain_fac) + pre_rut) CoD: 0.92076 RMS: 0.458721
22	rut = ((drain_fac + tanh(((traffic / (tanh(((drain_fac + (pre_rut + drain_fac)) / traffic)) - (tanh(drain_fac) / traffic))) / (drain_fac + ((tanh(pre_rut) + (MSN + sqrt(traffic))) + drain_fac))))) + pre_rut) CoD: 0.923291 RMS: 0.448844
23	rut = ((drain_fac + ((pre_rut / (tanh(((pre_rut / (tanh(exp(drain_fac)) - MSN)) / (drain_fac + tanh(((((drain_fac + pre_rut) / traffic) - log(sqrt((pre_rut * pre_crack)))) / (MSN / pre_rut)))))) - MSN)) / (MSN / traffic))) + pre_rut) CoD: 0.926163 RMS: 0.432804
24	rut = ((drain_fac + ((pre_rut / (tanh((((pre_rut / log((MSN + 1.79365504))) / (pre_rut / tanh((MSN / (drain_fac + drain_fac))))) / (exp((log(MSN) -

	(drain_fac / MSN))) - pre_rut))) - (1.76302934 + traffic))) / (MSN / traffic))) + pre_rut) CoD: 0.926818 RMS: 0.42435
25	rut = ((tanh(((((drain_fac + pre_rut) / pre_crack) / (MSN - pre_rut)) / ((((age + ((tanh(tanh(tanh((age - pre_crack)))) / pre_rut) / pre_rut)) / (sqrt(pre_rut) + tanh(pre_crack))) + pre_crack) + (drain_fac / drain_fac)))) + drain_fac) + pre_rut) CoD: 0.948802 RMS: 0.464496
26	rut = (pre_rut + (drain_fac + tanh(((pre_rut / (MSN - pre_rut)) / (MSN + (((((pre_rut + (drain_fac + tanh(((pre_rut / (MSN - pre_rut)) / ((age + drain_fac) + drain_fac))))) * MSN) + age) + (((MSN + pre_rut) * pre_rut) + age)) + sqrt(drain_fac))))))) CoD: 0.965953 RMS: 0.399738
27	rut = (pre_rut + (tanh(((pre_rut / (MSN - pre_rut)) / ((log(pre_rut) + (drain_fac + drain_fac)) + ((pre_rut + ((exp(MSN) + (sqrt(exp(drain_fac)) + drain_fac)) + ((pre_rut - pre_rut) - drain_fac))) - pre_rut)))) + drain_fac)) CoD: 0.963538 RMS: 0.388418
28	rut = (pre_rut + (tanh(((pre_rut / tanh((MSN - pre_rut))) / MSN)) + drain_fac)) CoD: 0.772911 RMS: 0.737751
29	rut = (pre_rut + (tanh(((pre_rut / tanh((MSN - pre_rut))) / ((pre_rut + (pre_crack / drain_fac)) + ((drain_fac + drain_fac) + ((exp(traffic) + MSN) / exp((sqrt((traffic + traffic)) / (drain_fac / -4.3765)))))))) + drain_fac)) CoD: 0.972522 RMS: 0.347012
30	rut = (pre_rut + (tanh(((pre_rut / tanh((MSN - pre_rut))) / ((pre_rut / (MSN + (MSN + tanh(((pre_rut / MSN) - tanh((((pre_rut + (exp(pre_rut) + MSN)) * age) / pre_rut))))))) + ((exp(MSN) + drain_fac) + MSN)))) + drain_fac)) CoD: 0.960358 RMS: 0.334246
31	rut = (tanh(((tanh(((tanh((pre_rut / drain_fac)) + drain_fac) / exp(MSN))) / tanh((MSN - pre_rut))) / (drain_fac + (pre_rut + drain_fac)))) + (pre_rut + drain_fac)) CoD: 0.960615 RMS: 0.420801
32	rut = (tanh(((tanh(exp((log(drain_fac) - sqrt(traffic)))) / tanh((MSN - pre_rut))) / ((pre_rut + drain_fac) + MSN))) + (pre_rut + drain_fac)) CoD: 0.965906 RMS: 0.391636
33	rut = (tanh(((pre_rut / tanh((MSN - pre_rut))) / ((((traffic + ((((traffic + ((age + MSN) + sqrt(MSN))) + (drain_fac + pre_rut)) + traffic) + traffic)) + ((MSN + age) + MSN)) + traffic) + drain_fac))) + (pre_rut + drain_fac)) CoD: 0.963928

	RMS: 0.356915
34	rut = ((pre_rut + drain_fac) + tanh(tanh(((pre_rut / tanh((MSN - pre_rut))) / ((((exp(MSN) + pre_rut) + (MSN - (MSN + MSN))) + exp(MSN)) + age))))) CoD: 0.961248 RMS: 0.360181
35	rut = (tanh(((pre_rut / tanh((MSN - pre_rut))) / (drain_fac + ((MSN + ((MSN / tanh(pre_rut)) + exp(MSN))) + (MSN + tanh(pre_rut)))))) + (pre_rut + drain_fac)) CoD: 0.964645 RMS: 0.331989
36	rut = (tanh(tanh(((pre_rut / tanh((MSN - pre_rut))) / ((drain_fac + (pre_rut / tanh((MSN - pre_rut)))) + ((exp(MSN) + pre_rut) + (drain_fac + (pre_rut - pre_rut))))))) + (pre_rut + drain_fac)) CoD: 0.954045 RMS: 0.347719
37	rut = (tanh(((pre_rut / (MSN - pre_rut)) / ((MSN - (tanh(((pre_rut / pre_rut) / pre_rut)) - (age * MSN))) + drain_fac))) + (pre_rut + drain_fac)) CoD: 0.960067 RMS: 0.396305
38	rut = (pre_rut + (drain_fac + tanh(((pre_rut / tanh((MSN - pre_rut))) / (((exp(MSN) + MSN) + ((MSN + tanh((tanh((tanh(MSN) + MSN)) + tanh(tanh(pre_rut))))) - pre_rut)) + (tanh(pre_crack) + MSN)))))) CoD: 0.96033 RMS: 0.322163
39	rut = ((drain_fac + tanh(((pre_rut / (MSN - (tanh((MSN - tanh(pre_rut))) + drain_fac))) / (((drain_fac + (tanh(pre_rut) + drain_fac)) + pre_rut) + exp(sqrt(age)))))) + pre_rut) CoD: 0.977974 RMS: 0.24396
40	rut = (pre_rut + ((tanh((traffic / (MSN - (tanh(drain_fac) + drain_fac)))) + drain_fac) + tanh(((tanh(((tanh(((tanh(traffic) / traffic) / ((tanh(traffic) + drain_fac) + drain_fac))) + drain_fac) / (drain_fac - pre_rut))) / pre_rut) / drain_fac)))) CoD: 0.972785 RMS: 0.261472
41	rut = ((drain_fac + tanh(((pre_rut / (drain_fac + (((age + drain_fac) + MSN) + ((age / drain_fac) + tanh(pre_rut))))) / (MSN - (tanh(drain_fac) + drain_fac))))) + pre_rut) CoD: 0.97987 RMS: 0.224582
42	rut = ((tanh(((pre_rut / (exp(MSN) + drain_fac)) / (MSN - (drain_fac + tanh(pre_rut))))) + drain_fac) + pre_rut) CoD: 0.977321 RMS: 0.23121
43	rut = ((tanh(((pre_rut / (exp(MSN) + (drain_fac + tanh(MSN)))) / (MSN - (drain_fac + tanh(age))))) + drain_fac) + pre_rut) CoD: 0.978665

	RMS: 0.226135
44	rut = ((drain_fac + tanh(((pre_rut / ((((pre_rut + sqrt(MSN)) + sqrt(drain_fac)) + ((sqrt(drain_fac) + (sqrt(pre_rut) + MSN)) + traffic)) + (sqrt(drain_fac) + (sqrt(pre_rut) + MSN)))) / (MSN - (tanh(drain_fac) + drain_fac))))) + pre_rut) CoD: 0.98158 RMS: 0.234279
45	rut = ((tanh(((pre_rut / ((((MSN - (tanh(drain_fac) + tanh(tanh(drain_fac)))) + MSN) + (age + (drain_fac + pre_rut))) + ((drain_fac + MSN) / (pre_rut + drain_fac)))) / (MSN - (tanh(drain_fac) + drain_fac)))) + drain_fac) + pre_rut) CoD: 0.979542 RMS: 0.231149
46	rut = (pre_rut + (drain_fac + tanh(((pre_rut / (((drain_fac + pre_rut) + age) + drain_fac)) / (MSN - (tanh(drain_fac) + drain_fac)))))) CoD: 0.976034 RMS: 0.246095
47	rut = ((drain_fac + tanh(((pre_rut / ((drain_fac + (tanh(tanh(exp(drain_fac))) + (MSN + (drain_fac + MSN)))) + pre_rut)) / (MSN - (drain_fac + tanh(drain_fac)))))) + pre_rut) CoD: 0.978682 RMS: 0.231445
48	rut = (pre_rut + (drain_fac + tanh(((tanh(pre_rut) / ((MSN + drain_fac) + tanh((pre_rut / ((drain_fac / ((drain_fac + pre_rut) + drain_fac)) + (pre_rut / MSN)))))) / (MSN - (tanh(drain_fac) + drain_fac)))))) CoD: 0.976256 RMS: 0.289925
49	rut = ((drain_fac + tanh(((pre_rut / ((exp(log(MSN)) * pre_rut) + tanh(pre_crack))) / (MSN - (drain_fac + tanh(pre_crack)))))) + pre_rut) CoD: 0.958696 RMS: 0.326981
50	rut = (pre_rut + (drain_fac + tanh(((pre_rut / (((log(drain_fac) + drain_fac) + drain_fac) + (tanh(pre_rut) + ((pre_rut + tanh(pre_rut)) + (pre_rut + (MSN + tanh(tanh(tanh(MSN))))))))) / (MSN - (tanh(drain_fac) + drain_fac)))))) CoD: 0.979913 RMS: 0.244445

Some of the Generations (out of 10000) Produced by GP kernel for Roughness Progression

1	dIRI = (((((RDS2 / RDS2) + exp((SNCK / RDS2))) / exp(IRI)) + (sqrt(IRI) + m)) + ((((sqrt(IRI) / ((SNCK / exp(IRI)) + AGE)) + exp((sqrt((dCRX / dCRX)) / (dPOT * AGE)))) / RDS2) + exp(YE4))) RMS: 0.983014 CoD: 0.50828
2	dIRI = (((SNCK / exp(IRI)) + (sqrt(IRI) + m)) + (((SNCK / RDS2) / RDS2) + exp(YE4))) RMS: 0.974038

	CoD: 0.504565
3	dIRI = (sqrt((((sqrt(log(IRI)) * YE4) + IRI) + (((exp(YE4) / RDS2) + ((RDS2 / RDS2) + exp((SNCK / exp(YE4))))) / RDS2))) + exp(YE4)) RMS: 0.979973 CoD: 0.5193
4	dIRI = (((((YE4 / RDS2) + exp((SNCK / RDS2))) / exp(IRI)) + (sqrt(IRI) + m)) + (((exp(YE4) + exp((sqrt((sqrt(IRI) + YE4)) / dCRX))) / (RDS2 * IRI)) + exp(YE4))) RMS: 0.950072 CoD: 0.502758
5	dIRI = (((IRI / IRI) + exp((YE4 * log((IRI / YE4))))) + ((((SNCK + RDS2) / (log(YE4) / log(IRI))) / exp(IRI)) + sqrt((((SNCK / RDS2) / log(IRI)) + (IRI / (exp(dCRX) - log(IRI))))))) RMS: 0.697016 CoD: 0.720021
6	dIRI = (exp((YE4 * log((IRI / YE4)))) - (YE4 - (sqrt((((SNCK / RDS2) / log(IRI)) + ((IRI / ((SNCK + IRI) / RDS2)) / (exp(dCRX) - log(IRI))))) + (((IRI + SNCK) / (log(YE4) / log(IRI))) / exp(IRI))))) RMS: 1.19457 CoD: 0.772762
7	dIRI = ((exp((log(IRI) * YE4)) + (IRI / IRI)) + (sqrt((((SNCK / RDS2) / log(IRI)) + (((IRI / dCRX) / dCRX) / dCRX))) + ((((SNCK + log(IRI)) / (log(YE4) / IRI)) / exp(IRI)) / dCRX))) RMS: 0.727298 CoD: 0.720186
8	dIRI = ((sqrt((((SNCK / RDS2) / log(IRI)) + ((((IRI / dCRX) / dCRX) / dCRX) / dCRX))) + ((((RDS2 + log(IRI)) / (log(YE4) / IRI)) / exp(IRI)) / dCRX)) + (exp((log(IRI) * YE4)) + (IRI / IRI))) RMS: 0.738723 CoD: 0.721877
9	dIRI = (exp((YE4 * log(IRI))) + (sqrt((((((IRI + IRI) / RDS2) / log(IRI)) / log(IRI)) + log(IRI))) + (((IRI / dCRX) / dCRX) / ((IRI / IRI) / (log(IRI) / SNCK))))) RMS: 0.657929 CoD: 0.71779
10	dIRI = ((sqrt((((((IRI + IRI) / RDS2) / log(IRI)) / log(IRI)) + log(IRI))) + ((((IRI / dCRX) / dCRX) / dCRX) / (dCRX / (log(IRI) / SNCK)))) + exp((YE4 * log(IRI)))) RMS: 0.663722 CoD: 0.718072
11	dIRI = ((sqrt((((((IRI + IRI) / RDS2) / log(IRI)) / log(IRI)) + log(IRI))) + ((((IRI / dCRX) / dCRX) / dCRX) / (dCRX / (log(IRI) / SNCK)))) + exp((YE4 * log(IRI)))) RMS: 0.663722 CoD: 0.718072
12	dIRI = (exp((YE4 * log(IRI))) + (sqrt((((((IRI + IRI) / RDS2) / log(IRI)) / log(IRI)) + log(IRI))) + ((((RDS2 / exp(((RDS2 / RDS2) * YE4))) / dCRX) / dCRX) / ((IRI / IRI) / (log(IRI) / SNCK))))) RMS: 0.65467 CoD: 0.729444
13	dIRI = (exp((log(IRI) * YE4)) + (sqrt(((((IRI / RDS2) / log(IRI)) / log(IRI)) +

	exp(log(log(IRI))))) + ((IRI / RDS1) / dCRX))) RMS: 0.710227 CoD: 0.701621
14	dIRI = ((sqrt(((((log((RDS1 + (((IRI / RDS1) / dCRX) + SNCK))) / RDS2) / log(IRI)) / log(IRI)) + (((RDS1 / dPOT) + IRI) / RDS2))) + ((IRI / RDS1) / dCRX)) + exp((log(IRI) * YE4))) RMS: 0.646073 CoD: 0.747139
15	dIRI = ((((IRI / RDS1) / dCRX) + sqrt(((((log((RDS1 + (IRI / RDS2))) / RDS2) / log(IRI)) / log(IRI)) + (((RDS1 / dPOT) + (log(dPOT) / sqrt(YE4))) / RDS2)))) + exp((YE4 * log(IRI)))) RMS: 0.751787 CoD: 0.758484
16	dIRI = (exp((YE4 * log(IRI))) + (((IRI / RDS1) / dCRX) + sqrt(((((log(((sqrt(RDS1) + exp(IRI)) + RDS1)) / RDS2) / log(IRI)) / log(IRI)) + (((RDS1 / dPOT) + IRI) / RDS2))))) RMS: 0.637652 CoD: 0.741554
17	dIRI = ((sqrt(((((log(SNCK) / RDS2) / log(IRI)) / log(IRI)) + (((RDS1 / dPOT) + (log(IRI) / log((RDS1 + (YE4 * dPOT))))) / log(RDS2)))) + (((IRI / RDS1) / dCRX) / dCRX)) + exp((YE4 * log(IRI)))) RMS: 0.634599 CoD: 0.755912
18	dIRI = ((sqrt(((((sqrt(RDS1) / RDS2) / log(IRI)) / log(IRI)) + ((((RDS1 / dPOT) + IRI) + dCRX) / RDS2))) + (((RDS2 / RDS1) / dCRX) / dCRX)) + exp((log(IRI) * YE4))) RMS: 0.624514 CoD: 0.766224
19	dIRI = (exp((log(IRI) * YE4)) + (sqrt((((((RDS1 / dPOT) + (sqrt(IRI) / log(IRI))) + dCRX) / RDS2) + (((sqrt((IRI + log(SNCK))) / RDS2) / log(IRI)) / log(IRI)))) + (((IRI / RDS1) / dCRX) / dCRX))) RMS: 0.65395 CoD: 0.75776
20	dIRI = (exp((log(IRI) * YE4)) + (sqrt((((((RDS1 / dPOT) + (sqrt(IRI) / log(IRI))) + dCRX) / RDS2) + (((sqrt((IRI + log(SNCK))) / RDS2) / log(IRI)) / log(IRI)))) + (((IRI / RDS1) / dCRX) / dCRX))) RMS: 0.65395 CoD: 0.75776
21	dIRI = ((sqrt((IRI + (((sqrt((sqrt(dPOT) / YE4)) / RDS2) / log(IRI)) / log(IRI)))) + ((((IRI + (YE4 * (IRI / IRI))) / RDS1) / dCRX) / dCRX)) + exp((log(IRI) * YE4))) RMS: 0.734646 CoD: 0.741019
22	dIRI = ((sqrt(((((sqrt((IRI / YE4)) / RDS2) / log(IRI)) / log(IRI)) + IRI)) + (((IRI / RDS1) / dCRX) / dCRX)) + exp((log(IRI) * YE4))) RMS: 0.734686 CoD: 0.749539
23	dIRI = ((sqrt(((IRI / (log(RDS2) + ((IRI + YE4) / RDS1))) + (((IRI / RDS2) /

	log(sqrt(IRI))) / log(IRI)))) + ((((sqrt(IRI) + IRI) / RDS1) / ((YE4 / RDS1) + dCRX)) / dCRX)) + exp((log(IRI) * YE4))) RMS: 0.644924 CoD: 0.740853
24	dIRI = ((sqrt((IRI + (((sqrt(((RDS1 / RDS2) / YE4)) / RDS2) / log(IRI)) / log(IRI)))) + ((((((IRI + dCRX) / RDS1) / dCRX) / dCRX) / dCRX) / log(RDS2))) + exp((log(IRI) * YE4))) RMS: 0.665739 CoD: 0.739549
25	dIRI = ((sqrt(((((sqrt(((sqrt((IRI / YE4)) / RDS2) / log(IRI))) / RDS2) / log(IRI)) / log(IRI)) + IRI)) + (((((IRI + IRI) / RDS1) / dCRX) / RDS1) / dCRX)) + exp((log(IRI) * YE4))) RMS: 0.639272 CoD: 0.747573
26	dIRI = ((sqrt((IRI + (((sqrt(((RDS1 / RDS2) / YE4)) / RDS2) / log(IRI)) / log(IRI)))) + (((((IRI + IRI) / RDS1) / dCRX) / RDS1) / dCRX)) + exp((log(IRI) * YE4))) RMS: 0.65414 CoD: 0.762173
27	dIRI = (exp((log(IRI) * YE4)) + (sqrt(((((sqrt(((sqrt((RDS2 / YE4)) / RDS2) / log(IRI))) / RDS2) / log(IRI)) / log(IRI)) + IRI)) + (((((IRI + IRI) / RDS1) / dCRX) / RDS1) / dCRX))) RMS: 0.644184 CoD: 0.754732
28	dIRI = ((sqrt(((((sqrt(((sqrt((IRI / YE4)) / RDS2) / log(IRI))) / RDS2) / log(IRI)) / log(IRI)) + IRI)) + (((((IRI + IRI) / RDS1) / dCRX) / RDS1) / dCRX)) + exp((log(IRI) * YE4))) RMS: 0.639272 CoD: 0.747573
29	dIRI = ((((((IRI + (sqrt(IRI) / RDS1)) / RDS1) / dCRX) / dCRX) + sqrt(((((sqrt(((sqrt(IRI) / RDS2) / log(IRI))) / RDS2) / log(IRI)) / YE4) + log(RDS1)))) + exp((log(IRI) * YE4))) RMS: 0.651713 CoD: 0.754196
30	dIRI = (((((IRI / RDS1) / dCRX) / dCRX) + sqrt(((((sqrt(((log((IRI / YE4)) / (IRI + dCRX)) / log(IRI))) / RDS2) / log(IRI)) / YE4) + log(IRI)))) + exp((YE4 * log((IRI / YE4))))) RMS: 0.663407 CoD: 0.779409
31	dIRI = (exp((YE4 * log((IRI / YE4)))) + (((((IRI / RDS1) / dCRX) / dCRX) / dCRX) + sqrt(((((sqrt(((sqrt((IRI / (log(IRI) * exp(dPOT)))) / RDS2) / log(IRI))) / RDS2) / log(IRI)) / YE4) + log(IRI))))) RMS: 0.604516 CoD: 0.765343
32	dIRI = ((sqrt((log(IRI) + (((sqrt((((((IRI / IRI) / RDS1) / RDS2) / log(IRI)) / log(IRI))) / RDS2) / log(IRI)) / YE4))) + ((((IRI / RDS1) / dCRX) / dCRX) / dCRX)) + exp((YE4 * log((IRI / YE4))))) RMS: 0.593356

	CoD: 0.771631
33	dIRI = (exp((log((IRI / YE4)) * YE4)) + ((((IRI / RDS1) / dCRX) / dCRX) + sqrt(((((sqrt((((exp((IRI / RDS2)) / IRI) / dCRX) / log(IRI))) / RDS2) / log(IRI)) / YE4) + log(IRI))))) RMS: 0.624127 CoD: 0.779708
34	dIRI = (exp((log((IRI / YE4)) * YE4)) + (sqrt(((((exp((((exp(YE4) / RDS2) / YE4) * YE4)) / RDS2) / log(IRI)) / log(IRI)) + log(IRI))) + (((IRI / RDS1) / dCRX) / dCRX))) RMS: 0.645791 CoD: 0.73198
35	dIRI = ((sqrt(((((sqrt(((exp(YE4) / RDS2) / YE4)) / RDS2) / log(IRI)) / IRI) / YE4)) + ((((IRI / RDS1) / dCRX) / exp((YE4 * YE4))) / dCRX)) + exp((YE4 * log(((IRI / YE4) / YE4))))) RMS: 0.738155 CoD: 0.72482
36	dIRI = (((((IRI / RDS1) / dCRX) / ((dCRX + (YE4 * dCRX)) - log(exp(YE4)))) + sqrt((((sqrt(exp((YE4 * IRI))) / RDS2) / log(IRI)) / YE4))) + exp((YE4 * log((IRI / YE4))))) RMS: 0.665069 CoD: 0.748337
37	dIRI = ((sqrt((((sqrt(exp((YE4 * IRI))) / RDS2) / log(IRI)) / YE4)) + (((((IRI / RDS1) / YE4) / sqrt(((IRI / YE4) * sqrt(RDS1)))) / dCRX) / dCRX)) + exp((YE4 * log((IRI / YE4))))) RMS: 0.687184 CoD: 0.735263
38	dIRI = ((sqrt((((sqrt(sqrt(((exp((RDS1 / dPOT)) / dCRX) * YE4))) / RDS2) / log(IRI)) / YE4)) + ((((((IRI / IRI) / dCRX) / dCRX) / RDS1) / YE4) / dCRX)) + exp((YE4 * log((IRI / YE4))))) RMS: 0.693138 CoD: 0.777757
39	dIRI = (((((log(((IRI / RDS1) / sqrt(YE4))) / dCRX) / dCRX) / sqrt(sqrt(dCRX))) + sqrt((((sqrt(sqrt(((dCRX / YE4) / sqrt(YE4)))) / RDS2) / log(IRI)) / sqrt(YE4)))) + exp((log((IRI / YE4)) * YE4))) RMS: 0.757343 CoD: 0.694039
40	dIRI = (exp((log((IRI / YE4)) * YE4)) + ((((IRI / RDS1) / dCRX) / sqrt(sqrt(dCRX))) + sqrt((((sqrt(sqrt(((RDS1 + (IRI / YE4)) / log(IRI)))) / RDS2) / log(IRI)) / sqrt(YE4))))) RMS: 0.688069 CoD: 0.735249
41	dIRI = ((sqrt((((((((RDS1 / RDS1) / sqrt(YE4)) / dCRX) + (dCRX / ((IRI / RDS1) / YE4))) / RDS2) / log(IRI)) / sqrt(YE4))) + (((IRI / RDS1) / dCRX) / dCRX)) + exp((log(IRI) * sqrt(YE4)))) RMS: 0.699382 CoD: 0.776772
42	dIRI = (exp((log(IRI) * sqrt(sqrt(YE4)))) + (sqrt((((sqrt((IRI / sqrt(YE4))) / RDS2) /

	log(IRI)) / log(IRI))) + (((((IRI / RDS1) + ((IRI / IRI) / sqrt(YE4))) / RDS1) / dCRX) / dCRX))) RMS: 0.605216 CoD: 0.782083
43	dIRI = (exp((sqrt(sqrt(YE4)) * log(IRI))) + (sqrt((((sqrt(RDS1) / RDS2) / (sqrt(sqrt(sqrt(YE4))) * log(IRI))) / log(IRI))) + (((IRI / RDS1) / dCRX) / dCRX))) RMS: 0.620314 CoD: 0.764392
44	dIRI = ((sqrt((((sqrt(RDS1) / RDS2) / log(IRI)) / log(IRI))) + ((((((sqrt(IRI) + (log(IRI) * dCRX)) / RDS1) + (IRI / RDS1)) / RDS1) / dCRX) / dCRX)) + exp((log(IRI) * sqrt(sqrt(YE4))))) RMS: 0.620051 CoD: 0.78892
45	dIRI = (exp((sqrt(sqrt(YE4)) * log(IRI))) + (sqrt((((sqrt(RDS1) / RDS2) / log(IRI)) / log(IRI))) + ((((exp(((sqrt(sqrt((YE4 * IRI))) / RDS1) * sqrt(sqrt(sqrt((dPOT * dCRX)))))) / dCRX) / dCRX) / sqrt(YE4)) / RDS1))) RMS: 0.609034 CoD: 0.797587
46	dIRI = ((((((RDS1 / dCRX) / (sqrt(dCRX) * RDS1)) / dCRX) / (RDS1 * YE4)) + sqrt((((sqrt(RDS1) / RDS2) / (log(IRI) * exp(((YE4 / dCRX) / (RDS1 * IRI))))) / log(IRI)))) + exp((log(IRI) * sqrt(sqrt(YE4))))) RMS: 0.602886 CoD: 0.804592
47	dIRI = ((sqrt((((exp((dCRX * (IRI / 9.67368))) / RDS2) / log(IRI)) / log(IRI))) + (((((sqrt(sqrt((RDS2 / log(IRI)))) / YE4) / RDS1) / dCRX) / dCRX) / dCRX)) + exp((log(IRI) * sqrt(YE4)))) RMS: 0.626455 CoD: 0.818527
48	dIRI = ((sqrt((((exp((dCRX * (IRI / 7.557))) / RDS2) / log(IRI)) / log(IRI))) + (((((sqrt(IRI) / YE4) / RDS1) / dCRX) / exp((dCRX * (IRI / 8.62583)))) / dCRX)) + exp((sqrt(YE4) * log(IRI)))) RMS: 0.567965 CoD: 0.806773
49	dIRI = (exp((sqrt(YE4) * log(IRI))) + (sqrt((((exp((dCRX * (IRI / 8.63641))) / RDS2) / log(IRI)) / log(IRI))) + (((((sqrt(sqrt(9.94722)) / YE4) / RDS1) / dCRX) / dCRX) / dCRX))) RMS: 0.571545 CoD: 0.813018
50	dIRI = ((sqrt((((exp((dCRX * (IRI / 8.63641))) / RDS2) / log(IRI)) / log(IRI))) + (((((sqrt(sqrt(10.1618)) / YE4) / RDS1) / dCRX) / dCRX) / dCRX)) + exp((sqrt(YE4) * log(IRI)))) RMS: 0.571289 CoD: 0.812581

CHAPTER 6

CONCLUSIONS AND RECOMENDATIONS

6.1 CONCLUSIONS

The present study consists of developing the decision making pavement maintenance management system for urban road network of Patiala city using HDM-4 and soft computing techniques like neural networks and genetic programming. The following conclusions have been drawn on the basis of this study:

1. The work presented in Chapter 3 comprised the methodology proposed for development of PMMS for urban roads in Patiala, Punjab, India. The proposed PMMS methodology includes: identification and selection of the urban road network, collection of field data and database management, and calibration and validation of HDM-4 pavement deterioration models for local conditions. The procedures and equipments used for collection of various kinds of field data on sixteen pavement sections have been described. The data for vehicle fleet plying on the road network, maintenance and rehabilitation activities, cost data for various types of maintenance & rehabilitation works, and the road user cost data, as obtained from field and relevant government publications has been presented. The time series pavement distress data of cracking, ravelling, potholes, rutting & roughness have been collected for the year 2012, 2013, 2014 and 2015.
2. The HDM-4 road deterioration models have been calibrated and validated for selected 16 in service urban road sections under local conditions using the time series pavement distress data collected for the year 2012, 2013, 2014 and 2015. 'Window' methodology has been used for calibration of pavement distress models in this study. The suggested calibration coefficients for progression of various pavement deterioration models have been compared with the HDM-4 model for default calibration factors as unity.
3. The statistical indicators like coefficient of determination (R^2) and Root Mean Square Error (RMSE) have been calculated and the calibration factor corresponding to minimum RMSE and maximum R^2 have been suggested for the urban roads in each group according to the traffic and age. Generalized Calibration progression factor (GCF) based upon the average of 4 different sets depending upon road traffic and age have been calculated as K_{cpa} as 0.44, K_{pp} as 1.18, K_{vp} as 0.13, K_{rst} as 2.71 and K_{gp} as 2.45 for cracking, potholing, ravelling,

rutting & roughness respectively for the Patiala city. It has been observed the rate of progression of cracking and ravelling, are slower by 56% & 87%, respectively than those predicted by default HDM-4 models. However, the rate of progression of potholing, rutting and roughness is faster by 18%, 171% and 145% than that predicted by default calibration factor of 1.

4. The calibrated HDM-4 pavement deterioration models need to be validated before using the calibration factors for developing the PMMS in the present study. For validation purpose the observed and HDM-4 model predicted values of distresses for the year 2014 have been compared for all the road sections of urban network. The linear regression relationship between the observed and predicted distresses has been developed by plotting the scatter plots. The value of R^2 varies between 0.71- 0.92 and RMSE varies between 0.92 - 1.3 for all the validated models. This shows a good agreement between observed and predicted distresses and hence proves the adequacy of the calibrated HDM-4 deterioration models for the urban roads in the study area. Hence, the suggested calibration factors for HDM-4 pavement deterioration models holds good and shall be useful for developing the pavement maintenance management system for the urban road network.
5. Pavement management must be capable of being used in whole or in part by various technical and administrative levels of management in making decisions regarding both individual projects and an entire urban road network. In the present study, different aspects of project and network level PMMS have been studied using various application module of HDM-4. This application is concerned with the economic evaluation of one or more maintenance and rehabilitation alternatives. This application deals primarily with the prioritization of a defined long list of candidate pavement section into a multi-year work programme under defined budget constraints. The PMMS developed at project level and network level has been presented with different case studies showing the effect on pavement condition and maintenance cost requirements for the selected urban road network. As per the work presented in Chapter 4, it has been concluded that all the road sections taken in this study of Patiala city will be needing reconstruction work within 0 to 9 years if no maintenance and rehabilitation work is assigned to the road sections throughout the intervening period.
6. On the basis of the economic analysis summary presented in chapter 4, the optimum M&R strategy selected for sections UR03, UR07, UR08, UR09, UR010, UR012, UR013, UR014, UR015 and UR016 is Alternative 1 (Resealing 25 mm SBSD) and for all other sections

Alternative 2 (Thin overlay 25 mm SDBC) has been the optimum maintenance strategy with maximum NPV/CAP value.

7. A comparison of the NPV/CAP values indicates that the condition responsive maintenance strategy gives a higher NPV/CAP ratio than obtained in case of the scheduled maintenance strategy. Hence, maintenance decisions with condition responsive have been selected as an optimum M&R alternative.
8. Reducing budget levels have increasingly detrimental impact on the pavement condition of the urban road network which will increase the road user cost. The effect of different budget allocation levels on average pavement condition of the urban road network has been expressed by the average roughness value in terms of IRI in m/km. The average roughness value of IRI 7.67 m/km is predicted for the year 2025 in case of the low budget allocation of 50 million Indian rupees which is very high as compared to average IRI of 4.00 m/km in the same year with budget allocation of 150 million Indian rupees. These types of low budget allocations will definitely result in the increase in the road user cost. Thus, it may be concluded, that the reducing budget levels have increasingly detrimental impact on the pavement condition of the urban road network which will increase the road user cost.
9. It has been concluded on the basis of the case study of Patiala city road network that deferring the maintenance activities has a very detrimental impact on the overall condition of the urban road network. The value of roughness reaches 9.2 m/km in the year 2019 if the maintenance is delayed by 4 years but if the maintenance is triggered as per the respective intervention level, the value of IRI is around 3.65 m/km in the year 2019. This will result in very high vehicle operation cost for the road users. Therefore, the M&R activities should not be delayed much from the time they have been triggered by the respective intervention levels.
10. The two emerging soft computing techniques; neural network and GP have also been applied on the data set of 16 road sections of Patiala City for the prediction of pavement distress. Chapter 5 consits of five models developed using GP: Model1, Model2, Model3, Model4 and Model5 for Cracking Progression, Ravelling Progression, Potholes Progression, Rutting Progression and Roughness Progression, respectively, and five models using neual network: Model6, Model7, Model8, Model9 and Model10 for Cracking Progression, Ravelling Progression, Potholes Progression, Rutting Progression and Roughness Progression, respectively. The GP models have been trained using the data set of 2012 and 2013. The trained GP models have been validated using the dataset of 2014 and 2015. According to statistics, if a proposed model gives $R^2 > 80\%$, there is a well-built

correlation between predicted and measured values for the data available in the dataset. In the present study, all the developed models have the value of $R^2 > 80\%$. Neural network and GP models have been also compared with the help of fitness functions *i.e.*, R^2 and RMSE. In this chapter, we have also developed neural network model and architecture of neural network has been finalizing by trial and error method. The preliminary investigation for neural network has been started by randomly selecting the value of hyperparameters on the basis of knowledge gained from literature. It has been observed that GP models provide the value of R^2 is higher and RMSE is less as compared to neural network, when applied on validation data sets. The results obtained through network level pavement management analysis have been integrated with GIS and presented in a graphical format through GIS applications.

The Pavement Management System methodology developed in this study would be useful to the agencies in planning pavement maintenance strategies in a scientific manner, and to ensure rational utilization of limited maintenance funds. This PMMS methodology can be used by various technical and administrative officials of the agency, in making decisions for project level and network level pavement management. Graphical presentation of PMMS results through GIS applications will also be useful for gaining better support from decision-makers, for adequate and timely fund allocations for preservation of the road network.

6.2 RECOMMENDATIONS FOR FURTHER WORK

- In the present study, only vehicle operating cost was considered to be road user cost. In future, study of accident costs data can also be included to get more accurate road user costs data.
- The study may be extended to develop the PMMS for urban cities having pavement quality concrete roads.

LIST OF PUBLICATIONS

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