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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The functional condition of highway pavements deteriorates continuously due to repeated loads of vehicular traffic and environmental factors such as temperature, snow and frost. It causes discomfort to the passengers, reduces vehicular speed and increases the Road User Cost (RUC). Pavements deteriorate at a slow rate at the initial stage after the construction and then the rate increases rapidly with time. If the maintenance measures are not taken up at the appropriate time, the deterioration becomes severe after some time and huge funds are required for reconstruction (Stevens, 1985; O'Brien, 1989; Zimmerman, 1995; Labi and Sinha, 2005). Hence it is necessary to keep the pavements in good condition by using proper maintenance plan.

With the rapid increase in the road construction activities in the least and less developed countries including India, the total funds required for pavement maintenance is continuously increasing. A number of countries have failed to maintain their roads properly not only due to lack of funds but also due to the absence of maintenance system to use the available funds effectively. Thus there is a need to develop a system by which the existing road networks could be maintained to the desired serviceability.

Pavement Maintenance System (PMS) can help the decision makers to prioritize the pavement stretches on the basis of distresses, in deciding the maintenance activities to be taken up and also to allocate the available funds in an optimal manner for the same (Fwa et al., 1994; Alsugair and Al-Qudrah, 1998; Reddy and Veeraragavan, 2002). A number of PMS are available in the form of comprehensive packages, but most of them require huge database such as history of pavements and time-series data on pavement condition at regular intervals. Hence, there is need to develop a system which follows the existing methods used for maintaining the roads by the Public Works Departments (PWD) in various states, and try to strengthen them by making them effective, economic, flexible and methodical.

In any PMS, prioritization plays an important role for selecting the pavement stretches for maintenance when the funds available are limited. Though a number of prioritization techniques are available, it is necessary to use the appropriate one based on the constraints on availability of data. While maintaining the network comprises large number of stretches, it would be appropriate to take maintenance decisions on a group of stretches having similar distress characteristics. Hence, there is a need to classify the given stretches into optimum number of groups and those groups need to be ranked.

Pavement roughness is an overall indicator of the quality of a pavement and it adversely affects the vehicle riding quality. It is also being used in establishing the Maintenance and Rehabilitation (M&R) priorities when the budget available is limited (Gillespie, 1981; Sayers et al., 1986; Liu Wei et al., 2005). In addition, many countries use the road roughness as one of the primary components in calculating vehicle operating costs (CRRI, 1982; Kadiyali and Associates, 1991; Kadiyali, 2000). Many highway agencies currently use road roughness for not only to evaluate the functional performance of pavement but also to indicate quality standards during construction process (Al Suleiman et al., 1999). A few PMS predicts the roughness after the construction of overlay but none of them have included the prediction of roughness after repairing individual distress parameters as a part of maintenance activity, which will help the decisions makers to take the maintenance decisions based on the change in roughness levels. To do this, there is a need to develop a correlation between roughness and critical distress parameters and the same can be integrated in maintenance system. Though a number of researches have reported that roughness is manifested as a combined effect of different individual pavement distress parameters, such as cracking, potholes, raveling and rutting (Paterson, 1987; Rohde et al., 1999), not many studies have been carried out to predict the roughness as a function of all these distress parameters.

Measuring the roughness is difficult since it also depends on the vehicular characteristics in addition to the actual road roughness. Several agencies have tried to standardize the roughness measurement process for uniformity. Consequently, several instruments have been developed and standardized at a particular speed for the collection of pavement roughness data (Wambold et al., 1981; Sayers et al., 1986; Cundill, 1991; Morosiuk et al., 1992; Bennett, 1996). Among various instruments, Towed Fifth Wheel Bump Integrator is the most popular equipment being used by several developing countries because it is affordable, simple and also needs less frequent maintenance and calibration (Jordan and Young, 1980; Mrawira and Haas, 1996). It usually runs at a standardized speed of 32km/hr to measure roughness of pavements. However, it might not always be possible to run the equipment at the standardized speed on low category roads such as Village Roads, Other District Roads and Major District Roads and also on a few State Highways due to excessive pavement distresses and the heterogeneous traffic mix with a reasonable proportion constituting of slow moving vehicles. On primary road systems such as Expressways, National Highways and some of the State Highways the situation is different. As these roads are usually well constructed and properly maintained through timely interventions and are usually traveled by fast moving vehicles, the average speed of vehicles is high and sometimes it is difficult to run the Bump Integrator at the standard speed of 32kmph, which is rather slow compared to the speed of other vehicle. Thus it would be convenient if the Bump Integrator could be calibrated at various speeds, both higher and lower than the standard speed so that it could be used in all kinds of roads effectively.

The PWD of various states in India, follows certain systematic steps to take up road maintenance work under severe budget constraints. There is scope to improve the system by strengthening the decision making process with the data available usually with them. Finally, it is necessary to develop an user friendly software for maintaining the flexible pavement stretches by incorporating the prioritization, grouping techniques and roughness model so that the user is able to take the maintenance decisions easily, distribute the funds in a logical manner and predict the roughness after carrying out the maintenance operations.

1.2 OBJECTIVES OF THE PRESENT STUDY

This study intends to develop a system for maintaining the flexible pavements at network level by utilizing the available funds judiciously and effectively. The aim is also to develop relationship between roughness and all the pavement distresses so that impact of each one of them could be determined which is turn would help to take most appropriate decisions for maintenance. To fulfill this goal the following study objectives have been set:

- Review the available prioritization and clustering techniques and to identify the suitable one for the present study.

- Review critically, various relationships between road roughness and pavement distresses proposed by different researchers with a view to identify the drawbacks with the existing models.

- Conduct extensive field studies with regard to the roughness as well as the identified causative distress parameters at a given point of time covering different classes of highway sections.

- Develop the model for standardizing Bump Integrator readings at different operating speeds

- Establish the relationship between road roughness with the causative distress parameters

- Prioritize the pavement stretches using appropriate prioritization technique.

- Identify the homogenous road stretches through a uniquely formulated clustering technique and developing methodology to find the optimum number of pavement stretches.

- Develop a practical network level pavement management strategy using the outcome of the above stages and develop a user friendly computer interface for the user agencies.

1.3 SCOPE OF THE PRESENT STUDY

The present research study is limited to a few selected road stretches covering National Highways (NHs), State Highways (SHs), and Major District Roads (MDRs) in the state of Rajasthan. The usually observed distresses on Indian roads such as cracking, potholes, patching, rutting and raveling have been included in the present study. All the distresses would be measured in terms of extent and severity. Mathematical relationships are to be developed to express roughness in terms of these distress parameters collected at a point of time. In addition to above distresses, edge failure data in three severity levels are also included for taking maintenance decisions. Hence, it is very clear that the present study is based on the existing condition of pavement. To have sufficient amount of data for analysis, the stretches would be divided into smaller segments of 50 m each. To have variety, data would be collected from different classes of highways such as NHs, SHs and MDRs. Along with the pavement distress data, roughness data is to be collected using Bump Integrator. For establishing the sensitivity of the roughness with the operating speeds of the Bump Integrator, roughness data would be collected at different operating speeds and would be validated.

As there is a need to develop a systematic plan for maintenance of the pavement stretches, a prioritization technique has to be developed using fuzzy approach based on the collected pavement distress parameters. In the prioritization process weights of the various distress parameters play a major role. An expert opinion survey is to be conducted through questionnaire survey to determine the weights. For a large number of stretches in a network, the homogenous pavement stretches are to be grouped using the most appropriate available clustering technique and then are to be prioritized.

The scope this study also extended in the direction of developing a practical network level pavement management system using the data, models and techniques established during the present study.

1.4 ORGANIZATION OF THE THESIS

The First Chapter of the thesis establishes the background and need for the research activity along with the list of objectives, scope and the details of the thesis organization.

Summary of the literature review with regard to roughness models, prioritization techniques, clustering techniques etc are being presented in the Second Chapter of the thesis.

The Third Chapter of the thesis explains the methodology followed in the present study.

The Fourth Chapter of thesis deals with the details of the field studies and data collection. The details regarding the selection of pavement stretches, collection of various pavement distress parameters and roughness data on the selected pavement stretches have been included. Data collected for calibration of Bump Integrator using Machine for Evaluating Roughness using Low-cost INstrumentation (MERLIN) and the data collected for standardizing the Bump Integrator at various operating speeds was also presented. Data collected through the expert opinion survey for assessing the weights of the various functional distress parameters have also been included in this chapter.

The Fifth Chapter of the thesis deals with preliminary data analysis and development of relationship between roughness and distresses along with its validation. Calibration and model developed for standardizing the Bump Integrator at different operating speeds also presented. In addition, prediction of roughness from the individual distress parameters and changes in roughness levels due to maintenance activities have also been illustrated through suitable graphs.

In the Sixth Chapter, the process of prioritization and clustering of the pavement stretches for maintenance has been discussed. The details of analysis of expert opinion surveys have also been discussed in detail. In addition, an intuitively developed mechanism for finding Optimum Number of Clusters (ONC) is also included in this chapter.

The penultimate Chapter explains the features of the software developed for project level pavement management system. It also deals with the optimal utilization of budgetary resources.

The last Chapter of the thesis concludes the study with findings, conclusions, and scope for further research.

CHAPTER 2

LITERATURE REVIEW

2.1 BACKGROUND

The functional condition of a pavement stretch, which is also expressed in terms of serviceability, has been given its due importance after its inclusion in the American Association of State Highway Officials (AASHO) flexible pavement design equation (HRB, 1962). AASHO is presently known as American Association of State Highway and Transportation Officials (AASHTO). One of the primary factors that affect the serviceability is the pavement roughness. Accordingly, researchers have developed number of models between serviceability and roughness. A few mathematical relationships have also been developed to correlate the serviceability with some of the pavement distress parameters. However, enough research has not been carried out for developing models, which are capable of expressing the roughness at a given point of time as a function of noticeable distresses usually measured by visual observation such as cracking, patching, raveling, potholes and rutting. But several studies such as Highway Development and Management system (HDM-3) (Paterson, 1987; Paterson, 1989), Central Road Research Institute (CRRI, 1994), HDM-4 (Odoki and Kerali, 2000), Brazil-United Nations Development Programme (UNDP) (Paterson, 1987; George, 2000), National Cooperative Highway Research Programme (NCHRP, 2001[2]), Transportation Road Research Laboratory (TRRL)-Kenya Model (Hodges, 1975; Linda and Robinson, 1982), Reddy (1996) and George (2000) developed roughness progression models by considering various combinations of influencing parameters , which were collected over a period of time.

As one of the objectives of the present study is to develop the model to predict the roughness from distresses at a given point of time, hence the summary of the studies carried out by various researchers in developing the relationships between roughness and distresses were reviewed. Models developed relating serviceability and distresses and relating serviceability and roughness has been also reviewed.

It has already been discussed in Chapter 1 that, the main objective of the current study is to develop a Pavement Maintenance System (PMS) for a given network of roads. In most of the developing countries including India, the funds available are usually limited for maintenance of road networks. In such situations, prioritization or ranking of pavement stretches plays an important role in PMS for distributing the funds optimally in a logical manner and thus various prioritization techniques have been reviewed in detail.

While dealing with a large number of stretches it would be practical and convenient to take maintenance decisions as a group or cluster of road stretches rather than according to individual ranks. Thus, clustering or grouping of homogeneous pavement stretches is important in PMS. Accordingly, a detailed literature survey has also been carried out on the available clustering techniques.

Keeping in view the vast literature available on each of the topics discussed above, and also on the objectives of the study, literature review has been presented in the following three sections.

- Roughness models
- Techniques for prioritization of the pavement stretches
- Techniques for clustering or grouping

2.2 ROUGHNESS MODELS

The "roughness" of a road is defined as the variations in elevation of surface that induce vibrations in traversing vehicles at a given point of time (Sayers et al., 1986). It directly affects the pavement serviceability and consequently affects the vehicle operating costs (fuel, oil, tyres, maintenance parts and labor, vehicle depreciation). Beyond a certain roughness value, the pavement deteriorates rapidly because of increased pounding action of heavy loads. As a result, it affects not only the speed of vehicles, safety and comfort of passengers but also the surface drainage characteristics (Abaynayaka et al., 1976; Sayers et al., 1986; Kadiyali and Viswanathan, 1992; Chandra, 2004).

While the road roughness is an important parameter in determining the performance of the pavements, it is also being used in establishing the Maintenance and Rehabilitation (M&R) priorities when the budget available is limited (Gillespie, 1981; Sayers et al., 1986; Liu Wei et al., 2005; Shahin, 2005). In addition, many countries use the road roughness as one of the primary components in calculating vehicle operating costs (CRRI, 1982; Kadiyali and Associates, 1991; Kadiyali, 2000). Many highway agencies currently use road roughness for not only to evaluate the functional performance of pavement but also as a quality assurance indicator during construction process (Al Suleiman et al., 1999).

Universally roughness is measured by International Roughness Index (IRI) and is expressed in metres per km. The complex mechanism and interaction between the roughness and various types of distresses has been shown in Fig 2.1 (Paterson, 1987). It may be observed from the figure that the road pavement deterioration is principally a combined effect of traffic and weather. Traffic loads induce stresses and strains within the pavement layers.

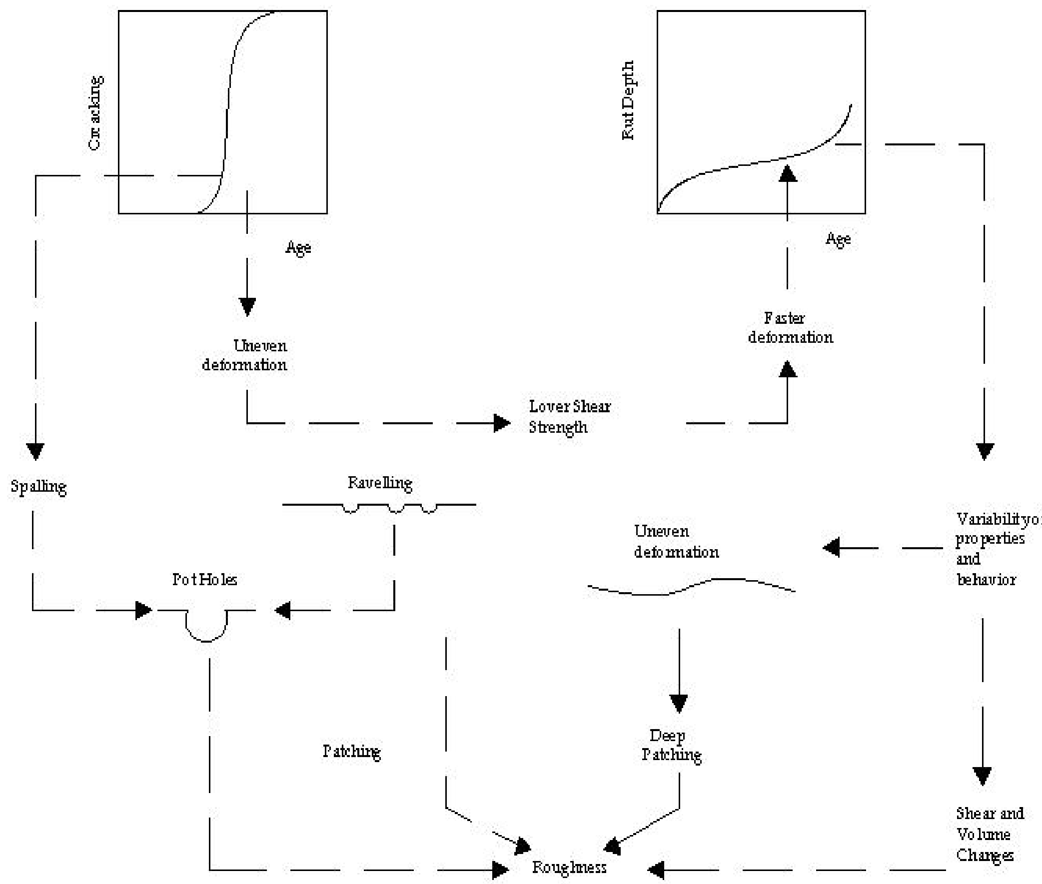


Fig 2.1: The Mechanism and Interaction of Distresses in Paved Roads

(Source: Paterson, 1987)

Under repeated loadings, these stresses and strains cause cracking in bound materials and deformation in all layers. Due to weather and seasonal temperature changes, oxidation of bitumen takes place and cause raveling. Once the cracking and raveling are initiated, they expand in both extent and severity with time and eventually potholes are formed. Open cracks further allow surface water to infiltrate the pavement layers and hasten the process of disintegration, reducing the shear strength of the bound materials and increase the rate of deformation under traffic. The cumulative deformation under wheel loads manifests itself in wheel path rutting. The chain distress mechanisms and combination of various modes of distresses result in roughness. In addition to the above distresses, patching, which is laid on the defect surfaces, also contributes to roughness.

It was also reported by Rohde et al. (1998) that roughness has been usually manifested as a combined effect of different individual pavement deterioration parameters such as cracking, potholes, raveling, patching and rutting and it further increases by weather and seasonal changes. They have also expressed the interaction among various types of distresses through simple graphical representation as shown in Fig 2.2. It might be observed from the figure that cracking and raveling initiate and progresses, and eventually potholes form. These three distresses contribute to roughness. In addition to this rutting, structural deformation and environmental effects also contribute to roughness. Al-Omari and Darter (1995); Hassan et al. (1999) have also stated that, the individual pavement distress parameters and the roughness compliment each other. That is to say that the increase in individual deterioration parameters result in increasing roughness, which once again acts as a catalyst in further deterioration of the pavement.

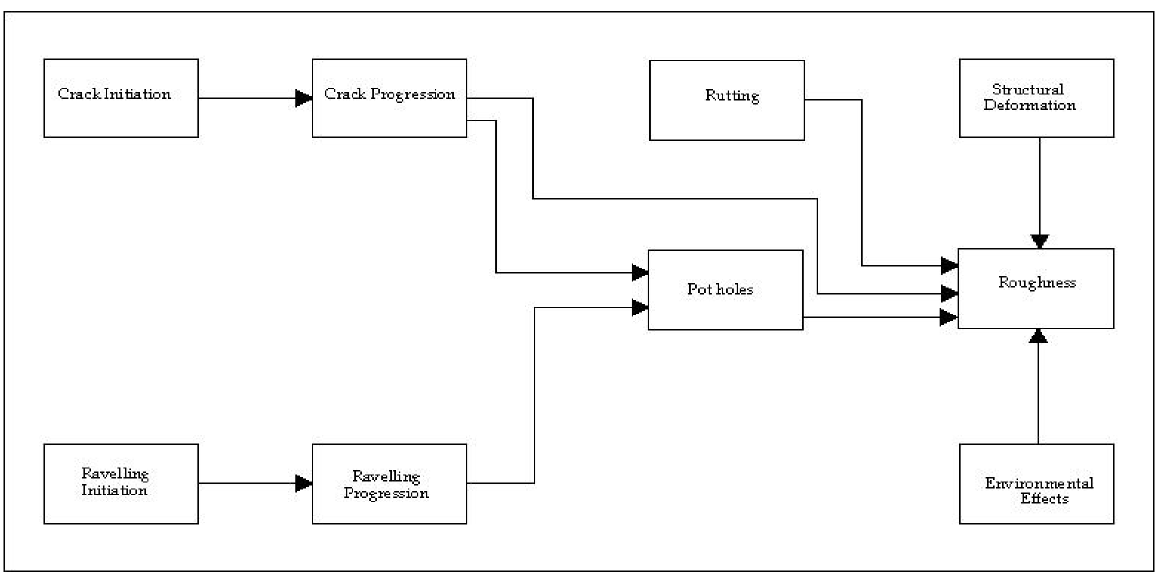


Fig. 2.2: Interaction between Various Types of Distresses (source: Rohde et al., 1999)

Numbers of researchers have developed models related to pavement roughness over the years. They may be classified under the following sections.

- Models predict the roughness using pavement distresses at a point of time
- Models correlate the serviceability and pavement distresses
- Models correlate the roughness and serviceability

2.2.1 Prediction of Roughness from Distresses at a given Point of Time

As already discussed, roughness on the pavement is mainly due to various distresses present on the surface of the pavement at a given point of time. Different models developed by various researchers have been presented in Table 2.1 and each one of them is discussed separately.

Two different models have been developed by Al-Omari and Darter (1995) for predicting roughness. They correlated IRI with the rut depth in one model and standard deviation of rut depth in another one. It has been reported that the contribution of rutting on the pavement roughness was not significant on the uniformly rutted surfaces, but it might not be true when wide ranges of rut depth values were considered. They have also investigated the effect of few other pavement distresses such as transverse cracking, potholes, depressions and swells. It is reported that all of them had significant effect on roughness. However, they haven't developed any relationship between roughness and these distresses.

Based on the study conducted in Egypt, Sharaf and Fathy (1998) have developed a relationship between IRI and Pavement Condition Index (PCI). The PCI has been calculated from the pavement distress data and which was mathematically expressed as shown in Equation 2.1.

Table 2.1: Roughness Models Developed from Pavement Distress Parameters

S. No	Developed by	Model Description
1	Al-Omari and Darter (1995)	IRI = 57.56*RD – 334 IRI = 136.19*SD – 116.36 IRI =International Roughness Index in cm/km RD = rut depth in mm SD = standard deviation of rut depth along the pavement
2	Sharaf and Fathy (1998)	IRI = 0.15 (100 – PCI) IRI =International Roughness Index in m/km PCI= Pavement Condition Index
3	Mactutis et al., (2000)	IRI = 0.597 (Initial IRI) + 0.0094 (Fatigue %) + 0.00847 (Rut depth) + 0.382 IRI =International Roughness Index in m/km Rut depth = Rut depth for both the wheel paths in mm Fatigue % = Percentage fatigue cracking
4	NCHRP (2001[1])	*Flexible Pavement Smoothness Model* $IRI = IRI_I + 0.134SDRut + 0.0029*T_{LL} + 0.0016F_L + 0.0207PI*RAINDEX – 0.000303P_{200} + 0.000831B_L – 0.0129Rut + 0.00094BL_M + 0.0195PI – 0.0071P_{0.02}$ IRI_I = initial IRI, m/km SDRut = Standard deviation of rut depth, mm T_{LL} = Transverse cracking (all severities), m

		F_L = Fatigue cracking (all severities), m^2 RAINDEX = Standard deviation of annual precipitation/annual precipitation*PI PI = Plasticity Index Rain = Annual precipitation, mm P_{200} = Percent of subgrade passing 0.075-mm sieve, % Rut = rut depth, mm B_L = Block cracking (all severities), m^2 BL_M = Bleeding (medium- and high-severity), m^2 $P_{0.02}$ = Percent of subgrade material passing 0.02 mm sieve, percent
5	NCHRP (2001[1])	*Overlaid Flexible Pavement Smoothness Model* $IRI = IRI_I + 0.0284RT_{LL} - 0.0098T_{NM} + 0.0028F_L + 1.04P_{NM} + 0.051T_{NH} + 0.00014FI + 0.0029LWP_L + 0.0058P_{0.02} - 0.000092Rain - 0.0082PI$ IRI_I = Initial IRI, m/km RT_{LL} = Transverse cracking (all severities), m T_{NM} = number of medium- and high-severity transverse cracks F_L = fatigue cracking (all severities), m^2 P_{NM} = number of medium- and high-severity patching T_{NH} = number of high-severity transverse cracks FI = Freeze index, °F-days LWP_L = longitudinal cracking (all severities) in the wheel path, m $P_{0.02}$ = percent of subgrade material passing 0.02-mm sieve, % Rain = annual precipitation, mm PI = plasticity index

6	NCHRP (2001[2])	*Conventional Flexible Pavement with thick Granular Base* $IRI = IRI_0 + 0.0463[SF(e^{age/20}-1)] + 0.00119(TC_L)_T + 0.1834(COV_{RD})+0.00384(FC)_T + 0.00736(BC)_T + 0.00155(LC_{SNWP})_{MH}$ IRI_0 = IRI measured within six months after construction, m/km $(TC_L)_T$ = Total length of transverse cracks (low, medium, and high severity levels), m/km (COV_{RD})= Rut depth coefficient of variation, percent. $(FC)_T$ = Total area of fatigue cracking (low, medium, and high severity levels), percent of wheel path area, % $(BC)_T$= Total area of block cracking (low, medium, and high severity levels), Percent of total lane area, % $(LC_{SNWP})_{MH}$ = Medium and high severity sealed longitudinal cracks outside the Wheel path, m/km. Age = Age after construction, years $SF = \frac{[(R_{SD})(P_{0.075}+1)(PI)]}{2*10^4} + \frac{[(\ln(FI+1)(P_{0.02}+1)(\ln(R_m+1)]}{10}$ R_{SD}= Standard deviation in the monthly rainfall, mm. R_m = Average annual rainfall, mm.

		$P_{0.075}$ = Percent passing the 0.075mm sieve. $P_{0.02}$ = Percent passing the 0.02mm sieve. PI = Plasticity Index FI = Average annual freezing index
7	NCHRP (2001[2])	*Deep Strength Pavements-Flexible Pavement with Asphalt treated Base* $IRI = IRI_0 + 0.0099947(Age) + 0.0005183(FI) + 0.00235(FC)_T + 18.36[1/ (TC_s)_H] + 0.9694(P)_H$ IRI_0 = IRI measured within six months after construction, m/km Age = Age after construction, years FI = Average annual freezing index. $(FC)_T$ = Total area of fatigue cracking (low, medium, and high severity levels), percent of wheel path area, % $(TC_S)_H$ = Average spacing of high severity transverse cracks, m. $(P)_H$ = Area of high severity patches, percent of total lane area, %.
8	NCHRP (2001[2])	*Semi Rigid Pavements (Flexible Pavement with Cement treated Base)* $IRI = IRI_0 + 0.00732(FC)_T + 0.07647(SD_{RD}) + 0.0001449(TC_L)_T + 0.00842(BC)_T + 0.0002115(LC_{NWP})_{MH}$ IRI_0 = IRI measured within six months after construction, m/km $(FC)_T$ = Total area of fatigue cracking (low, medium, and high severity levels), percent of wheel path area, %

		(SD_{RD}) = Standard deviation of the rut depth, mm $(TC_L)_T$ = Total length of transverse cracks (low, medium, and high severity levels), m/km $(BC)_T$= Total area of block cracking (low, medium, and high severity levels), Percent of total lane area, % $(LC_{NWP})_{MH}$ = Medium and high severity longitudinal cracks outside the wheel path area, m/km.
9	Dewan and Smith (2002)	IRI = 0.0171 (153 – PCI) IRI is in m/km PCI = f(Fatigue cracking, Block cracking, wheel path & non-wheel path Longitudinal cracking, Transverse cracking, Patch / Patch deterioration, Shoving, Raveling, Rutting data)
10	Jyh-Dong Lin et al. (2003)	This model is developed using Artificial Neural Networks IRI= f (Rutting, Alligator cracking, Cracking, Digging /patching , Potholes, Corrugation, Man-holes Stripping, Patching, Bleeding)

$$PCI = 100 - \sum_{i=1}^{n} DeductValue_i \quad (2.1)$$

Where,

PCI = Pavement Condition Index

n = number of observable distresses, and

Deduct Value = (Wt for distress) *(Wt. for severity)*(Wt. for Extent)

This model is apparently quite simple and easy to use. However, for calculating deduct values they have assigned weights to all distress parameters, hence success of the model depends on how accurately weights are being considered.

Using the data obtained form the WesTrack project, conducted in Reno, Nevada, Mactutis et al., (2000) developed a relationship between IRI and pavement distresses. The distresses such as fatigue cracking (% area), rut depth (mm) and roughness were measured at regular intervals after applying every 5 million equivalent single axle loads. Initial IRI (m/km) was measured before conducting the experiment. With this data a relationship was developed by considering the initial IRI (m/km), fatigue cracking and rutting as dependent variables and roughness as independent variable. It was reported that, the initial IRI had strong effect on roughness. It might be observed from the equation that the coefficients of fatigue cracking and rutting were almost same. It reveals that although both the variables measured in different units, the impact was almost same if their magnitudes were equal. Also, the constant value of 0.382 was on the higher side, which suggested that all the distress parameters were not considered and a few other factors were also to be involved in the prediction of IRI, which were not considered.

Based on the data collected as part of Long Term Pavement Performance (LTTP) studies, NCHRP (2001[1]) developed a series of models to predict the pavement roughness from the distresses. While developing this model initial IRI, frost heave, subgrade swelling, pavement distresses such as cracking, standard deviation of rut depth, bleeding, rut depth were considered as dependent variables and measured IRI as independent variable. Two separate models were presented for the original flexible pavement and overlaid flexible pavements. It was reported that the initial roughness had strong effect and standard deviation of the rut depth had significant effect on the pavement roughness at a given point of time. It might be observed from the equation that the coefficient of standard deviation of rut depth was quite high compared to other variables considered in the study. The R^2 value obtained was 0.5 for the newly constructed pavement and 0.79 for the overlaid pavements. It shows that the correlations were moderately explained by the equations. It might be possible to develop a more statistical significant equation if all the possible distresses had been considered.

To improve the regression statistics, the roughness prediction models presented in NCHRP (2001[1]) were modified and new models were presented in NCHRP (2001[2]) by considering the additional independent variable such as the type of the material used for construction of base course layer. They reported that base course type was found to be an important variable that significantly improved on the regression statistics and accordingly, different models were developed for conventional flexible pavement with thick granular base, deep strength flexible pavement with asphalt treated base and semi rigid pavements (Flexible Pavement with Cement treated Base). Though the additional variable for improving the regression statistics was used, effect of that variable was not appreciable on predicting roughness.

To estimate the Vehicle Operating Costs (VOCs) using roughness on the roads in San Francisco Bay area, Dewan and Smith (2002) have established a correlation between pavement roughness and PCI. In this study also PCI was calculated using the Eq. 2.1 by considering various distresses such as fatigue cracking, block cracking, longitudinal cracking (wheel path and non-wheel path), transverse cracking, patch / patch deterioration, shoving, raveling, rutting data etc. This model is almost similar to the model developed by Sharaf and Fathy (1998) as discussed earlier. They reported that there was a strong correlation between roughness and PCI. However, the weights of various distresses play an important role in the accuracy of the model.

To evaluate the applicability of IRI as an overall representation of pavement performance, Jyh-Dong Lin et al. (2003) correlated IRI and pavement distresses by using Feed Forward Back-Propagation (FFBP) neural network methodology. They considered pavement distresses such as rutting, alligator cracking, cracking, patching, potholes, corrugation, man-holes, stripping and bleeding as input variables and roughness as an output variable. Based on the weights obtained from the neural network architecture they have reported that potholes, patching and rutting have the highest correlation; man-holes, stripping, and corrugation have less correlation; cracking, alligator cracking and bleeding have least correlated with IRI. However, they did not follow any particular procedure to fix the number of neurons in the hidden layer of neural network and it was done on the basis of trial and error.

2.2.2 Relationship between Serviceability and Distress Parameters

Pavement serviceability refers to the ability of a pavement to provide desired level of service to the users and it depends on pavement condition. The serviceability performance concept was developed in 1960's in AASHO road test which was carried out to evaluate the pavement performance in terms of riding quality (HRB, 1962; Patterson, 1987). This indicator first appeared as a rating made by users based on the condition of the road. This was represented by a subjective index called Present Serviceability Rating (PSR) and later was replaced by an objective index called Present Serviceability Index (PSI). This is determined by applying the rating given by the users based on riding quality of a stretch of road. They rate on a scale of 0 to 5, where 5 means an excellent riding quality and zero scale indicates a very poor riding quality (Fwa, 2005). Keeping in view the fact that the riding quality depends on the pavement distresses, several researches and agencies have developed relationships between them. The models such developed are summarized in Table 2.2 and are being discussed below.

Model developed in AASHO road test (HRB, 1962; AASHTO, 1993) considered the distresses such as crack length, slope variance, rut depth and patching as dependent variables and PSI as independent variable. Serviceability equation, developed by Darter and Barenberg (1976) considered different types of cracking, patching and rut depth variances. TRRL study concluded that the PSI depended on pavement roughness, cracking and patching (Hodges et al. 1975). In India CRRI (1977) developed two models for predicting PSI. One model was purely based on the roughness and the other was based on the roughness, cracking and patching. AASHO serviceability equation was modified by Uzan and Lytton (1982) and they reported that the variance of rut depth was more important parameter in influencing the PSI. They replaced the slope variance with rut depth variance. Al-Omari and Darter (1995) have developed a relationship to predict PSI from the distresses such as depressions, potholes, cracking and average rut depth.

A close look at the above studies reveals that majority have not considered important distresses such as potholes and raveling, in developing the models.

Table 2.2: Relationship between Serviceability and Pavement Distress Parameters

1	HRB, 1962; AASHTO, 1993	$PSI=5.03-1.91 \log(1+SV)-0.01(C+P)^{0.5} - 1.38\ RD^2$ PSI = Present Serviceability Index SV = Slope Variance C = major cracking in ft per 1000 sq ft area P = Bituminous patching in sq ft per 1000 sq ft area RD = rut depth measured in inches over 4ft span embracing each wheel track (average rut depth of both wheel paths in inches measured at the center) of a 4-ft span in the most deeply rutted part of the wheel path $SV=\frac{\sum Y^2 - \frac{1}{n}\left(\sum Y\right)^2}{n-1}$ Where, Y = difference between two elevations 9 in. apart n = number of elevation readings
2	FHWA Zero-Maintenance Pavements Study (Darter and Barenberg, 1976)	$PSR = 4.5 - 0.49RD - 1.16RDV^{0.5}(1 - 0.087RD\ V^{0.5}) - 0.13 \log(1+TC) - 0.0344(AC+P)^{0.5}$ RD = rut depth in both wheel paths of the pavement, in RDV = rut depth variance, in^2 *100 AC = class 2 or class 3 alligator or fatigue cracking, ft^2 /1000ft^2 TC = transverse and longitudinal cracking, ft^2 /1000ft^2 P = patching, ft^2 /1000ft^2

3	TRRL Study (Hodges et al., 1975)	$PSI=5.41-1.8 \log (0.40*R_t - 30)-1.01 (C+P)^{0.5}$ $R_t = 0.0634*R$ Where, R= Roughness obtained by Bump Integrator in mm/km C = (Cracked area in %)*10 P = (Patched area in %)*10
4	CRRI (1977)	By considering roughness alone $PSI=13.315-3.943 \log R$ By considering roughness and surface distresses $PSI=12.479-3.57\log R-0.0205D$ R= Unevenness Index, cm/km D= Pavement surface distress (Cracking and Patching area in sqm/100sq.m)
5	Uzan and Lytton (1982)	$PSI = 4.436 - 1.686 \log_{10}(1+350 Var(RD)) - 0.881 RD^{2.5}- 0.031(C+P)^{0.5}$ where, Var(RD) = Rut depth Variance RD = average rut depth of two wheel paths; and C+P = area of cracking plus patching in ft^2 per 1000 ft^2.
6	Al-Omari and Darter (1995)	$PSR = 4.95 - 0.685D - 0.334P - 0.051C - 0.211RD$ D = number of high-severity depressions (number per 50 m) P = number of high-severity potholes (number per 50 m) C = number of high-severity cracks (number per 50 m) RD = average rut depth, mm

However, these distresses are very common on the State Highways (SHs), Major District Roads (MDRs) and Other District Roads (ODRs) in India. Sometimes, they are also observed on a few National Highways (NHs). These parameters have a substantial contribution on PSI value of a stretch of road. Thus, none of above equations would be suitable for Indian roads as they are. In addition, none of the researchers have studied the influence of severity of distress on PSI.

2.2.3 Relationships between Serviceability and Roughness

The Present Serviceability Indices (PSI) developed by various researchers as discussed in section 2.2.2 may not be directly applicable in Indian conditions as a few key pavement distress parameters such as raveling, potholes have not been considered in any of those models. Though, PSI is sensitive to many parameters, but the studies have shown that it is highly correlated and could be easily predicted through roughness values (Hass et al., 1994). This process also avoids the assessment of PSI through raters as their perception might be different. Hence, in this section relationships developed between PSI and roughness by different researchers were reviewed with a view to identify the most suitable model for prediction of PSI in Indian situations. These relations are presented in Table 2.3 and are being discussed below in detail.

Using the data collected from different countries and by involving number of raters, a non-linear model was developed by Paterson (1986) for calculating the PSI form the IRI, which is shown in S.No.1 in Table 2.3. With a simple modification, Gillespie (1992) developed a linear model to correlate the PSI and IRI. Using the data collected from the states of Indiana, Louisiana, Michigan, New Mexico, and Ohio on both flexible and rigid pavements, Al-Omari and Darter (1994) developed another non-linear model which was almost similar to Paterson (1986) model.

Models thus developed were examined by Gulen et al., (1994) and they reported that those equations were statistically incorrect. The reason given by them was that the equations were biased because they were forced to pass through PSI equal to 5 when IRI value was zero. They conducted a study on 20 randomly selected pavement stretches and developed a relationship between PSI and IRI, where the constant value was 9 in place of 5 as compared to all other cases.

As a part of predicting the remaining service life of pavements based on present roughness data, Al-Suleiman and Shiyab (2003) correlated PSI and IRI based on the data collected on asphalt-surfaced pavements in Dubai. They developed two separate equations for fast and slow lanes (heavy trafficked). The reason given by them was that deteriorating process and traffic conditions were different in these two types of lanes. However, both the equations yielded almost similar results.

Based on a study carried out over Chilean roads, de Solminihac et al. (2003) developed two mathematical equations explaining relationship between PSI and IRI, in one case PSI was obtained through raters and in another case it was calculated using AASHTO (1993) equation. These relations were compared with the other similar relations developed by Paterson (1986) and Al-Omari and Darter (1994) and it was found that the developed relationship based on the PSI through the raters was predicting higher values, whereas PSI found through AASHTO equation was almost matching as obtained by using other relationships.

A comparative analysis was done by representing the equations developed by various researchers as presented in Table 2.3 in graphical form (Fig. 2.3).

Table 2.3: Relationship between Serviceability and Roughness

S. No	Developed by	Model Description
1	Paterson, (1986)	$PSI = 5e^{-(IRI/5.5)}$ PSI = Present Serviceability Index for each homogenous roughness section. IRI = The mean IRI of the homogenous roughness section.
2	Gillespie (1992)	PSI= 5.0 - IRI/100 for 0 < IRI < 300 (in/mile) IRI= International Roughness Index in inch/mile
3	Al-Omari and Darter (1994)	$PSI = 5e^{-(IRI/3.85)}$ IRI= International Roughness Index in mm/m
4	Gulen et al., (1994)	$PSI=9.0e^{(-0.557*IRI)}$ IRI= International Roughness Index in mm/m
5	Al-suleiman and Shiyab, (2003)	$PSI = 5\exp^{(-0.2533 IRI_S)}$ $PSI = 5\exp^{(-0.2021 IRI_F)}$ IRI_S, IRI_f = International Roughness Index of the pavement (mm/m or m/km) for slow and fast lanes, respectively.
6	*d*e Solminihac et al., (2003)	$PSI_{CHILE} = 5.772 - 1.132\sqrt{IRI}$ $PSI_{AASTHO} = 5.671 - 1.714\sqrt{IRI}$ IRI = International Roughness Index in m/km

Where PSI was taken as ordinate and roughness as abscissa. The roughness values vary from 1 to 10 m/km with a uniform increment to calculate the corresponding PSI values.

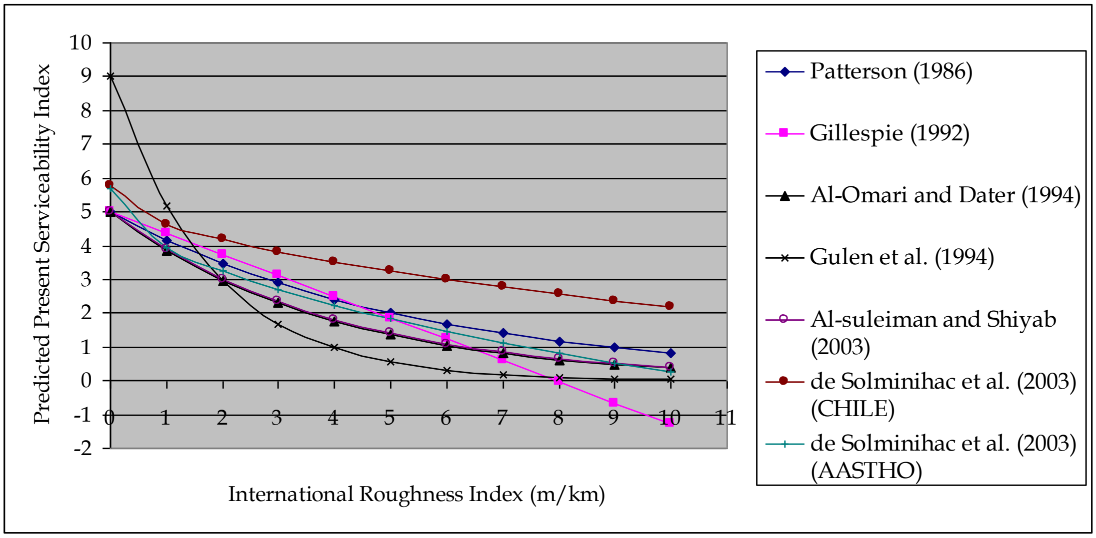


Fig 2.3: Prediction of PSI Values from IRI Values Using Relations Developed by Various Researchers

It may be observed that the PSI values calculated using Paterson (1986) model decrease at a uniform rate as the roughness increases. The models developed by Al-Omari and Dater (1994) and Al-Suleiman and Shiyab (2003) predict almost same PSI values for different roughness values. The model developed by Gillespie (1992) gives negative values if roughness is more than 8 m/km. Model presented by Gulen et al. (1994) predicts high PSI values when the roughness is low and suddenly decrease up to IRI of 3 m/km and then it decreases gradually. Model developed by *de* Solminihac (2003) (AASTHO) is almost similar to Paterson (1986) model up to the IRI value of 12m/km and beyond that model gives negative PSI values which is absurd.

Comparing all the models, it is observed that Gillespie (1992) and *de* Solminihac (2003) models would not be suitable for Indian conditions where high roughness values on low category roads are common. Model developed by Gulen et al. (1994) does not predict PSI values uniformly. Relationship developed by Paterson (1986) would be the most suitable for predicting PSI from the IRI values where data is collected from different class of road stretches having varying magnitude of IRI. For developing the model a large amount of data from different countries and number of raters were collected while finding the PSI. Though, the relations developed by Al-Omari and Darter (1994) and Al-Suleiman and Shiyab (2003) also predict slightly lower PSI values as compared to Paterson model, they might not be suitable as these models were developed based on the data collected in a particular country only.

2.2.4 Observations from Roughness and Serviceability Models and Research Gap

While the distress parameters such as cracking, potholes, rutting, raveling and patching directly affect the IRI value, the impact of each distress in terms of extent and severity needs to be considered to develop a model which would be practical in Indian context. This would also help the decision makers to identify the major contributing parameters causing road roughness and accordingly higher priority could be given in correcting these distress parameters.

Sometimes, maintenance decisions may also be taken based on the PSI values. The review of literature shows that most of the relationships developed between PSI and distresses may not be suitable for Indian conditions as they have neglected few distress parameters which are quite common on Indian roads. However, model developed by Paterson (1986) is robust enough to be applied in Indian conditions as data collected for developing that model was from number of developing and developed countries.

2.3 PRIORITIZATION TECHNIQUES FOR PAVEMENT MAINTENANCE

For developing any Pavement Maintenance Management System (PMMS), one of the important steps is the prioritization of the pavement stretches based on their deterioration levels. To identify the most suitable prioritization technique a thorough literature review has been carried out to study the available ones.

Priority analysis is a systematic process that determines the best ranking list of candidate sections for maintenance based on specific criteria such as pavement condition, traffic level and pavement function *etc*. (Ramadhan et al., 1999). Prioritization becomes an effective tool for supporting decisions to be taken for effective pavement management. The management system strives to achieve the maximum benefits through prioritization (Tighe et al., 2004). Also, the quality of priority setting can directly influence the effectiveness of available resources, which, in most cases, is the primary judgment of the decision maker (Sharaf, 1993).

Number of researches have used different methods for prioritization of pavements for maintenance. These methods have been categorized in the following groups and have been discussed separately under different sections.

- Condition Indices
- Fuzzy approach
- Other techniques like Geographical Information System and Analytical Hierarchy Process

2.3.1 Prioritization using Condition Indices

The condition indices are the numerical indices developed for prioritizing pavement stretches which required maintenance by assigning weights to various pavement distresses and traffic and were ranked according to these indices (Haas et al., 1994). Based on the Maintenance Index (MI) and Safety Index (SI), Rufford et al. (1980) have prioritized the pavement stretches, where, MI was considered as a function of deflection, visual pavement distresses, roughness and SI as a function of skid resistance and roughness. These indices were calculated by giving ratings to various variables based on their extent. However, they have neglected the severity of ditresses. Pavement stretches were also prioritized by using indices such as Pavement Condition Index (PCI) (Uzarski, 1984) and Defect Rating Index (DRI) (Snaith and Burrow, 1984). These indices were calculated based on the various distresses present on the surface of the pavement by assigning suitable weights on them. It was observed that the weights were expressed in quantifiable terms irrespective of the presents of uncertainty. Priority Ratings were developed by Fwa et al. (1989) for routine maintenance of highways at the district and sub-district levels, based on a study conducted for the Indiana Department of Highways. They were determined by assigning weight factors to the various pavement distress parameters and the functional class of highway. The use of Composite Index (CI) for prioritization was demonstrated by Chen et al. (1993) and they claimed that the technique had yielded optimal solutions. In all these studies, the extent and severity of failures were considered and were expressed in quantifiable terms. The prioritization would entirely depend on the accuracy of weights and ratings given to each variable considered.

Based on the data collected from the Egyptian road network, Sharaf (1993) developed a priority index, which was defined as a function of defect length, traffic factor and defect factor as shown in equation 3.2.

$$\text{Priority index} = DL / (TF * DF) \tag{3.2}$$

Where, DL= Defect Length i.e length of the road need maintenance

TF= Traffic factor

DF= Defect Factor

The traffic factor values of 0.1, 0.5, and 1.0 were taken on the basis of average daily traffic and defect factors varied from 0.1 to 1.0 were considered based on the type of defect. It might be observed from the equation that less the defect factor higher is the priority index. The author did not explain clearly how the defect factors for various distresses were derived. Defect factor for pothole was less compared to other distresses considered for developing Priority Index.

Based on the Present Serviceability Rating (PSR), Benkelman Beam Deflection (BBD), Unevenness Index (UI) and traffic, Veeraragavan and Justo (1994) formulated two different guidelines while fixing priorities for strengthening and resurfacing of pavements. They suggested that the stretches with high characteristic deflections and heavy traffic loads were to be strengthened on a high priority. Stretches with high UI or low PSR values and high traffic volume were to be resurfaced on a high priority basis. They also suggested the threshold values for deflection and traffic volume, which were arrived at based on the data collected on urban roads. These values might not be valid for other types of roads.

Ministry of Transportation of Ontario (MTO) used the overall performance index called Pavement Condition Index (PCI) for prioritization which was defined as a function of Riding Comfort Rating (RCR) and Distress Manifestation Index (DMI) (Helali et al., 1996). In this study RCR was a measure of the riding quality of the pavement surface as perceived by the traveling public and DMI was a composite subjective measure of extent and severity of pavement distress manifestation. DMI has been calculated on the basis of weighting factors given to density and severity of distresses. The accuracy of the model would depend on the perception of road users and the weights put on the distress parameters.

It was suggested by Jain et al. (2001) that decision regarding maintenance of roads could be taken on the basis of Present Serviceability Index (PSI). It was calculated by measuring some of the serviceability parameters such as roughness, rutting, cracking, skid resistance and potholes. Severity of distresses was not considered in this study.

Ranking of pavement stretches at network level based on Priority Ranking Model (PRM) was suggested by Reddy & Veeraragavan (2002). In their studies, five pavement distresses such as cracking, potholes, unevenness, patched area and rut depth were directly measured in the field and their weights were established in direct quantifiable terms by conducting an expert opinion surveys. The ranking was done based on Priority Index (PI) which was a function of the Pavement Distress Index (PDI) and prioritization factor. The study showed that, the weight on the cracking was quite high compared to other distresses, which was unusual provided the distresses such as potholes and patching were present on the pavement surface. They also did not consider the severity of distresses while prioritizing pavement stretches.

Using Priority Score Tighe et al. (2004) prioritized the airport pavement sections. It was a function of Pavement Condition Index (PCI), Traffic, Operational Sensitivity (OS) and Functional Classification. They had given weights for all these parameters and priority score was calculated, accordingly, the PCI represented the condition of the pavement and it got maximum weightage compared to all the parameters considered in the study.

2.3.2 Prioritization using Fuzzy Approach

Numerous researches have used fuzzy approach for ranking or prioritizing in various decision-making processes, such as, location of the distribution centre from the different alternatives (Chen, 2001), land suitability analysis for agricultural crops by addressing the uncertainty (Prakash, 2003), auto road construction (Sanja & Radivoj, 2002) and selection of service provider (Mei-Fang Chen et al.(2003). However enough attempts have not been made to prioritize pavement stretches for maintenance decisions. Fuzzy approach was used by Bandara and Gunaratne (2001) for prioritizing pavement stretches for current and future maintenance decisions. They expressed extent of various distresses and their weights in linguistic variables and then applied the fuzzy logic. They applied fuzzy logic for determining both the severity and extent of pavement distresses. For maintaining low volume roads constructed under Prdhan Mantri Gram Sadak Yogana, in India Chandran et. Al. (2007) has been used fuzzy logic. They reported that to avoid the human errors in quantifying the extent and severity of distresses fuzzy logic is handy. In their study they have considered roughness, skid resistance and pavement distress for prioritizing the pavement stretches. However, roughness is mainly due to the presence of distresses on the surface and hence including both roughness and distresses may not be required.

2.3.3 Prioritization using Other Techniques

Using the Pavement Performance Study (PPS) and Road User Costs (RUCs) models developed for Indian roads, Sharma and Pandey (1997) developed a methodology for taking decisions on maintenance investments. PPS models were used to predict the condition of the pavement and based on it road user cost was calculated. Then the stretches were prioritized by calculating benefits in terms of decreasing road user cost. While the approach is quite relevant, the initial data requirement is very high.

Analytical Hierarchy Process (AHP) was used by Ramadhan et al., (1999) for pavement maintenance priority ranking. They used AHP for determining the weights of various priority factors, such as, road class, pavement condition, operating traffic, riding quality, safety condition, maintenance cost and importance to community. Ranking was done on the basis of Priority Index, which was a function of priority factors and then weights.

Based on pavement condition data, Aggarwal et al., (2001); Karandikar et al., (2003) and Jain et al., (2003) have demonstrated the use of Geographical Information System (GIS) in taking decisions related to maintenance. They reported that it was an important tool in a decision support system by facilitating the preparation, analysis, display and management of highway data in a geographical platform. The prioritization of stretches was based on the Pavement Condition Index (PCI).

Based on the Pavement Structural Evaluation (PSE) value, Hossain et al., (2002) have prioritized pavement stretches. It was a function of pavement deflection which was obtained by Falling Weight Deflectometer (FWD), age, thickness and surface distress. They considered only cracking type of distress and reported that other types of distresses were not significant.

Highway Development and Management (HDM-4) tool was used by Singh and Sreenivasulu (2005) for prioritizing the road sections. It was done on the basis of Net Present Value (NPV) and cost ratio by inputting the traffic and various pavement related variables such as roughness, rutting, Benkelman Beam Deflection (BBD), cracking, potholes and edge failures in HDM-4 model. Though this system is powerful for optimizing the budgetary constrains, it requires a large amount of data which is difficult to get in most of the developing countries.

2.3.4 Observations on Prioritization Techniques and Research gap

Pavement distresses and their weights play a vital role in prioritizing the stretches but severities of distresses were not considered in most of the works and the weights were assigned by the authors themselves. In some case, the expert opinion survey was conducted and weights were expressed in quantifiable terms. However, it is difficult even for the expert to put definite weight on each parameter as some uncertainty always plays in their mind.

It was also observed that some of the important distresses such as potholes and raveling were not considered in most of the studies conducted in developed countries. It might be due to non existence of those parameters on the pavements of developed countries where proper maintenance is done on a regular basis. However, such kind of distresses are very common on Indian roads. Hence, consideration of the distress parameters such as cracking, raveling, potholes, patching, rutting and edge failure would be most appropriate for Indian conditions. The extent and severity of any kind of distress affects the functional condition of the pavement. An effective maintenance management could be developed, provided the extent and severity of each pavement distress could be measured accurately. While it is not very difficult to measure the extent in the field by visual observations, the severity cannot be quantified so easily. It would be appropriate to measure the severity of each parameter on a language scale and then to convert them into quantifiable terms using fuzzy logic.

2.4 REVIEW OF VARIOUS CLUSTERING TECHNIQUES FOR GROUPING OF PAVEMENT STRETCHES

Clustering is a division of data into groups of similar objects. Each group, called a cluster, consists of objects that are similar to one another and dissimilar to objects of the other groups (Jain et al., 1999). This is an important process in pattern recognition and machine learning (Hamerly and Elkan, 2002[1]). Many diverse techniques have been developed in order to discover similar groups in large datasets, out of which, Hierarchical and Partitional techniques are being widely used (Mahamed, 2004; Han and Kamber, 2001). Hierarchical algorithms create a hierarchical decomposition of the objects into either agglomerative (bottom-up) or divisive (top-down). On one hand, agglomerative algorithms start with each object being a separate cluster by itself and successively merge groups according to a distance measure. The clustering may stop when all objects are in a single group or at any other point where the user wants. On the other hand, divisive algorithms follow the opposite strategy. They start with one group of all objects and successively split groups into smaller ones, until each object falls into one cluster, or as desired. The hierarchical algorithms are highly user friendly in the sense that there is no need to specify the number of clusters at the beginning. However, it suffers with major limitations of being static in nature i.e, not being accommodative in moving a pattern assigned from one cluster to another. In addition, it is also computationally complicated (Mahamed, 2004; Turi, 2001).

Partitional clustering algorithm constructs partitions of the data, where each cluster optimizes a clustering criterion, such as, the minimization of the sum of squared distance from the mean within each cluster. The distance measure usually employed is the Euclidean distance. A close look into the hierarchical and partitional algorithms indicates very clearly that the limitations of one technique are being explained by other technique. However, the partitional clustering algorithm needs the number of clusters to be specified at the beginning itself unlike in the hierarchical algorithm (Mahamed, 2004). Though it looks to be a limitation, the flexibility is being offered by partitional algorithm in moving a given pattern from one cluster to other cluster in a dynamically iterative manner. Due to this dynamism, this has been the preferred choice by various researchers for variety of application (Jain et al., 1999). In addition, partitional algorithms are being observed to be very accurate in comparison with hierarchical techniques, especially in the pattern recognition (Jain et al., 1999). It is with this background that these techniques have been used in the present research activity.

Though number of specific techniques has been developed within the domain of partitional clustering algorithm, K-Means technique has been the preferred choice because of its simple use and efficiency (Mahamed, 2004; Turi, 2001). However, most of the clustering algorithms including K-means require the user to specify the number of clusters in advance (Hamerly and Elkan, 2002(2); Lee and Antonsson, 2000). Finding the optimum number of clusters is often an *ad hoc* decision, based on prior knowledge, assumptions, and practical experience (Hamerly and Elkan, 2002(2)). The problem of finding optimum number of clusters in a dataset has been the subject of research (Halkidi, et al., 2001). However, the outcome is still unsatisfactory in this area (Rosenberger and Chehdi, 2002).

2.4.1 Observations from Clustering Techniques and Research Gap

After reviewing various clustering techniques, it has been decided to use K-Means clustering technique for grouping the pavement stretches because of its easy application, accuracy and effective handling of a large amount of data. However, it was observed that user need to define the number of clusters as many researchers were unable to suggest the method to find the same.

2.5 SUMMARY

In the current chapter, different relationships developed between roughness and pavement distresses, serviceability and pavement distresses, roughness and serviceability were reviewed. Also, various prioritization and clustering techniques were reviewed. Based on this, observations of the existing methods were discussed and research gap was identified.

CHAPTER 3

METHODOLOGY

3.1 BACKGROUND

The review of literature in the preceding chapter brings out the following points

The distress parameters such as cracking, potholes, rutting, raveling and patching directly affect the IRI value and the impact of each distress in terms of extent and severity needs to be considered to develop a suitable model.

Some of the important distresses such as potholes and raveling were not considered in most of the studies conducted in developed countries in developing the relationship between roughness and pavement distresses. It might be due to non existence of those parameters on the pavements where proper maintenance is usually done on a regular basis. However, such kind of distresses are very common on Indian roads and need to be considered for Indian conditions.

Also, most of the relationships developed between PSI and distresses might not be suitable for Indian conditions as they neglected few distress parameters which are quite common on Indian roads.

Pavement distresses and their weights play a vital role in prioritizing the stretches but in most of the works the weights were assigned by the authors themselves. In some cases, the expert opinion survey was conducted and weights were expressed in quantifiable terms. However, it is difficult even for the experts to put definite weight on each parameter as some uncertainty always plays in their mind and thus there is scope to introduce Fuzzy Logic for expressing the weights of the distresses.

While it is not very difficult to measure the extent in the field by visual observations, the severity cannot be quantified so easily. It would be appropriate to measure the severity of each parameter on a language scale and then to convert them into quantifiable terms using fuzzy logic.

Even though a number of clustering techniques are available in the literature, use of K- Means clustering technique for grouping the pavement stretches would be most appropriate because of its easy applicability, accuracy and capability to effectively handling a large quantity of data. However, it was observed that user needs to define the optimum number of clusters depending on the volume of data.

Based on the above observations, it was decided to develop a simple Pavement Maintenance System (PMS) in the present study, for maintaining the network of roads at a desired level of service by taking logical and appropriate decisions under budgetary constraints. As many of the developing countries, including India, have limited budget for maintaining the network of roads, the system would be ideal tool for the use of Public Works Department (PWD) of the state governments. The present system proposed in this study primarily follows the existing methods used for maintaining the road networks by the PWD and tries to strengthen them by making them effective and methodical. Relationship between roughness and various distresses have been developed so that the roughness could be predicted on the basis of kind of repair work to be taken up. This is expected to help the decision makers to study the impact of decisions in advance and then to take appropriate maintenance measures within the limited budget.

Also, keeping in view the fact that in some cases pavement condition is expressed in terms of Present Serviceability Index (PSI), it would be predicted using the most appropriate of the existing relationships developed by various researchers between International Roughness Index (IRI) and PSI.

3.2 Methodology followed in the present study

A step wise methodology depicted in the Fig 3.1 has been planned in this study.

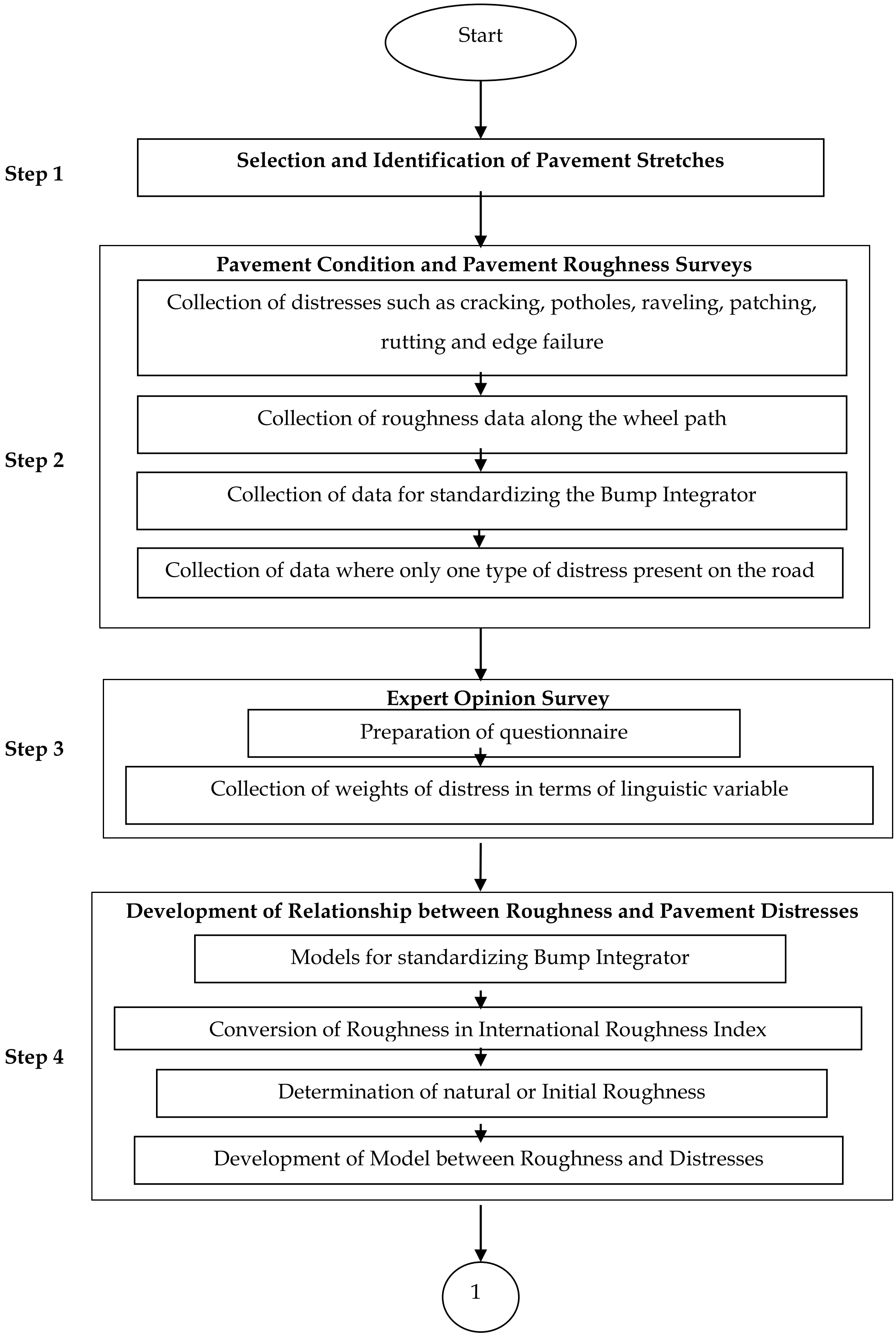
Step 1: Selection and Identification of Road Stretches

While dealing with a large network of roads for maintenance, the first step is to develop an identification method of the links. This might be achieved by a methodical numbering system. The objective should be to identify the concerned road stretch by looking at the identification number. There should be an in-built system so that the kind of road e.g. National Highways (NHs) , State Highways (SHs) and any other kind could also be made out from the identification number. In the present study, a limited number of stretches were considered and it was not needed to develop an elaborate numbering system. However, the road stretches have been identified on the basis of highway number and chainage.

Step 2: Pavement Condition and Pavement Roughness Surveys

On the selected stretches flexible pavement distresses such as cracking, raveling, pothole, patching, rutting and edge failures data in terms of extent and severity would be collected by visual inspection. In addition, roughness data would be collected along the wheel path using Bump Integrator.

While collecting roughness data using Bump Integrator it might not be possible to maintain the standard operating speed of 32 km/hr on some of the stretches due to poor pavement condition and heterogeneity of traffic.


Start
Step 1
Selection and Identification of Pavement Stretches
Pavement Condition and Pavement Roughness Surveys
Collection of distresses such as cracking, potholes, raveling, patching, rutting and edge failure
Collection of roughness data along the wheel path
Step 2
Collection of data for standardizing the Bump Integrator
Collection of data where only one type of distress present on the road
Expert Opinion Survey
Step 3
Preparation of questionnaire
Collection of weights of distress in terms of linguistic variable
Development of Relationship between Roughness and Pavement Distresses
Models for standardizing Bump Integrator
Conversion of Roughness in International Roughness Index
Step 4
Determination of natural or Initial Roughness
Development of Model between Roughness and Distresses
1

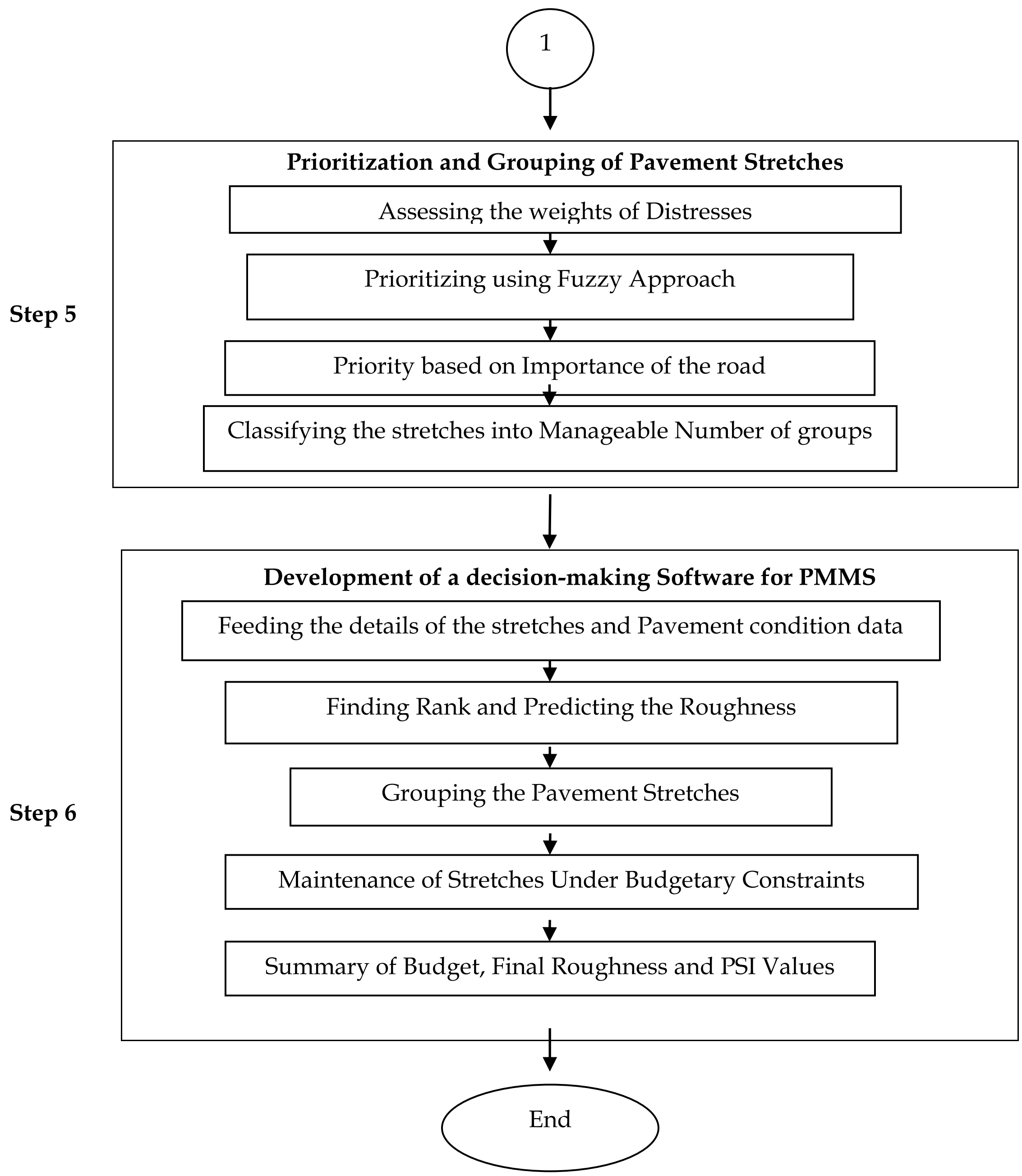


Fig 3.1: Various Steps Followed in the Present Study

Sometimes it is also difficult to maintain the desired speed on busy roads such as NHs due to high speed vehicles. Hence, the Bump Integrator would be standardized at different operating speeds, so that roughness data could be collected on any stretch at any convenient speed.

Keeping in view the fact that each kind of distress would have different impact on the overall roughness of a pavement stretch, data would be collected on stretches where only one kind of distress is visible, so that its individual impact could be determined.

Step 3: Expert Opinion Survey

Distress parameters data to be collected in terms of extent and severity may not have same impact on the functional condition, which plays vital role in prioritizing the stretches for maintenance. Hence an expert opinion survey would be conducted to ascertain the weights of various distresses by sending a specially prepared questionnaire to a few selected experts having field and academic backgrounds. As it would be difficult to express the weights of distresses in quantifiable terms due to the presence of uncertainty or fuzziness, experts would be asked to express them on linguistic scale.

Step 4: Development of Relationship between Roughness and Pavement Distresses

Initially, models would be developed for standardizing the Bump Integrator at different operating speeds. The roughness collected at any speed other than the standard operation speed of 32km/hr would be corrected using this model.

Universally roughness is expressed in terms of International Roughness Index (IRI); hence the roughness obtained from the Bump Integrator would be converted into IRI and then used in the model development. The roughness obtained on the pavement surface is the sum of the initial roughness and due to the distresses. Accordingly, initial roughness would be determined on the newly laid or overlaid pavement stretches on different functional classes of highways and the same would be deducted from the total roughness to determine the contribution of distresses on overall roughness.

Using the pavement roughness and distresses in terms of extent and severity data collected over sufficiently large number of varying stretches, relationships would be developed between them.

Step 5: Prioritization and Grouping of Pavement Stretches

Prioritization of pavement stretches plays an important role in PMS, especially when funds available for maintenance are limited. The stretches would be prioritized on the basis of the distress data collected over entire width of the pavement stretch.

As already discussed in step 3, weights play an important role in prioritization process and it is difficult to assess them due to uncertain in nature. It was noted from the literature that, fuzzy logic could be an ideal tool to handle situations which are uncertain in nature, hence it would be used while assessing the weights of the distresses. Keeping in view the fact that the priority to be given would also depend on the importance of the road, a weighing system would be generated, which depends on the class of road and traffic volume.

While dealing with large number of stretches it would be necessary to rank the stretches group wise rather than individually for maintenance. Hence, the homogeneous stretches would be clustered or grouped into manageable numbers using available clustering technique and those will be ranked.

Step 6: Development of Decision-Making Software for PMS

User friendly software would be developed for maintaining the network of roads. The roughness model which is to be developed in step 4 and the prioritization and grouping process suggested in step 5 would be incorporated in the software. User needs to give the details of the stretches and distresses data collected over it. Based on this information the software would predict the roughness and rank the pavement stretches.

Software would be developed such that, user could take decisions regarding maintenance of the stretches rank wise or group wise. Depending on the availability of funds, user would have options to select the type of maintenance decision, either construction of overlay or repairing of the selected pavement distresses. Unit cost for repairing the various distresses would also be provided based on the current Basic Schedule of Rates (BSR) developed by PWD, Jhunjhunu District, Rajasthan.

The user would have option to decide about the basis of maintenance plan. For example, it might be decided to take maintenance decision with an objective of having all the stretches to have roughness less than threshold value or it might be to identify the stretches having the roughness values over a threshold and then repair them. There are many other ways the maintenance decision could be taken.

The process developed would be iterative in nature. Once the first set of maintenance decision has been taken, the software itself will calculate the funds needed. It would also determine the possible roughness values of the stretches to be improved and the whole process of prioritization would be repeated with all the stretches again. This process will continue until the funds are going to be exhausted. Finally, summary of budget, final roughness values and PSI would be presented in Microsoft Excel file.

CHAPTER 4

DATA COLLECTION

4.1 BACKGROUND

The methodology proposed for the current study to develop a Pavement Maintenance System (PMS) and relationship between roughness and distresses requires data to be collected through field and expert opinion surveys. Field surveys have been carried out to measure the roughness and flexible pavement distresses over the defined wheel path and entire width of the pavement. To develop the relationship between the pavement roughness and distresses, data collected on defined wheel path was used and the data collected over entire width was used for taking decisions for maintenance. The expert opinion survey was conducted to find out the weights of the selected distresses.

Towed Fifth Wheel Bump Integrator was used in the present study to measure the pavement roughness. This equipment was calibrated by the Central Road Research Institute (CRRI), New Delhi. It has been suggested in the operation manual that, it needs to be calibrated at regular intervals. Accordingly, it was decided to calibrate again with MERLIN (Machine for Evaluating Roughness using Low-cost INstrumentation) at Birla Institute of Technology and Science (BITS), Pilani prior to the collection of roughness data in the field.

While measuring the roughness in some of the locations, it was found difficult to maintain the standard operating speed of 32 km/hr due to poor condition of the pavement and heterogeneity of traffic. Hence, the need was felt to develop a relationship between the roughness at standard speed and that of obtained at different operating speeds. Accordingly data was collected at different operating speeds ranging from 10 to 50 km/hr with an increment of 5km/hr along with the standard operating speed of 32km/hr.

Various distress parameters do not have the same impact on the functional condition of the pavement, which plays a greater role while taking decisions related to maintenance activities. Hence, it was felt necessary to find out the weights of the distress parameters to assess the contribution of each on the overall pavement condition. Accordingly, an expert opinion survey was conducted to seek the opinion of experts with varying backgrounds.

It may be noted that this chapter only discusses the details of data collection process, the analysis of the data has been taken up in Chapters five and six.

4.2 COLLECTION OF PAVEMENT DISTRESS DATA

The data collection process in the present research was planned meticulously and implemented in the following stages.

4.2.1 Selection of Test Sections through Reconnaissance Survey

A detailed reconnaissance survey was conducted by visiting a number of roads of different functional classes covering two districts in the state of Rajasthan namely Jhunjhunu and Sikar. The study stretches were selected based on the following criteria:

- The stretches representing different classes of roads namely National Highways (NHs), State Highways (SHs) and Major District Roads (MDRs)
- The condition was essentially poor with at least one visible distress.
- They were free from interruptions in the form of intersections, cattle and pedestrian interference to ensure free traffic flow conditions
- Mostly on straight alignment i.e free from having vertical and horizontal curves

- All are flexible pavements and constructed on level ground with no cutting/filling

Based on the above criteria a total of 14 different stretches of variable lengths were chosen. To have sufficient data, they were divided into smaller pavement sections of 50m length each. Pavement distress data was collected on the wheel paths of both the left and right lanes separately. The lanes were designated left and right depending on the direction of data collection. Data was also collected over the entire width of the pavement for the same stretches. Details of stretches have been presented in Table 4.1. It might be observed that, out of the fourteen selected stretches of variable length representing different categories of roads, two on NHs, three on SHs and Nine on MDRs. The study area and the locations of road stretches have been shown in the maps in Fig. 4.1 and 4.2.

4.2.2 Selection of Flexible Pavement Distress Parameters and Levels of Severity

Variety of distress parameters present in terms of extent and severity affect the functional condition of pavements. After visiting a number of road stretches as a part of reconnaissance survey and also by interacting with the field engineers of the Public Works Department (PWD), six different distress parameters namely cracking, raveling, potholes, patching, rutting and edge failures have been identified as the major factors which affect the functional condition of flexible pavements. The extent and severity levels of the selected distress parameters also have varying effect on pavement condition. The extent of the distress parameters can be measured through visual observation, but it is difficult to quantify the severity that easily. Hence it was decided to classify severity in terms of low, medium and high. However, since the perception regarding the severity may vary from person to person and to avoid the discrepancy while collecting data, descriptions of the severity levels were clearly defined (Table 4.2) based on the studies carried out by various

Table 4.1: Details of the Stretches

S.No	Name of the Road	Class of the Road	Wheel Path	Chainage (km)		Length (km)	No. of Sections
				From	To		
1	Sikar – Jaipur	NH -11	Left	11	14	3	60
			Right	11	14	3	60
2	Reengas – Sikar	NH -11	Left	37	40	3	60
			Right	37	40	3	60
3	Singhana – Narnoul	SH-13	Left	9	11	2	40
			Right	9	11	2	40
4	Pachori – Singhana	SH-13	Left	0	0/950	0.95	19
			Right	0	0/950	0.95	19
5	Dumoli-Singhana	SH-13	Left	0	2/200	2.2	44
			Right	0	2/200	2.2	44
6	Pilani – Loharu	MDR-82	Left	2/549	2/949	0.4	8
			Right	2/549	2/949	0.4	8
7	Pilani – Loharu	MDR-82	Left	2/987	5/337	2.35	47
			Right	2/987	5/337	2.35	47
8	Pilani – Loharu	MDR-82	Left	5/417	6/267	0.85	17
			Right	5/417	6/267	0.85	17
9	Loharu – Pilani	MDR-82	Left	16/733	17/583	0.85	17
			Right	16/733	17/583	0.85	17
10	Loharu – Pilani	MDR-82	Left	17/663	20/013	2.35	47
			Right	17/663	20/013	2.35	47
11	Loharu – Pilani	MDR-82	Left	20/041	20/441	0.4	8
			Right	20/041	20/441	0.4	8
12	Pilani – Loharu	MDR-82	Left	12/300	13/500	1.2	22
			Right	12/300	13/500	1.2	22
13	Loharu – Pilani	MDR-82	Left	11/500	12/700	1.2	22
			Right	11/500	12/700	1.2	22
14	Pilani By-pass	MDR	Left	0	1	1.0	20
			Right	0	1	1.0	20
			Total				**858**

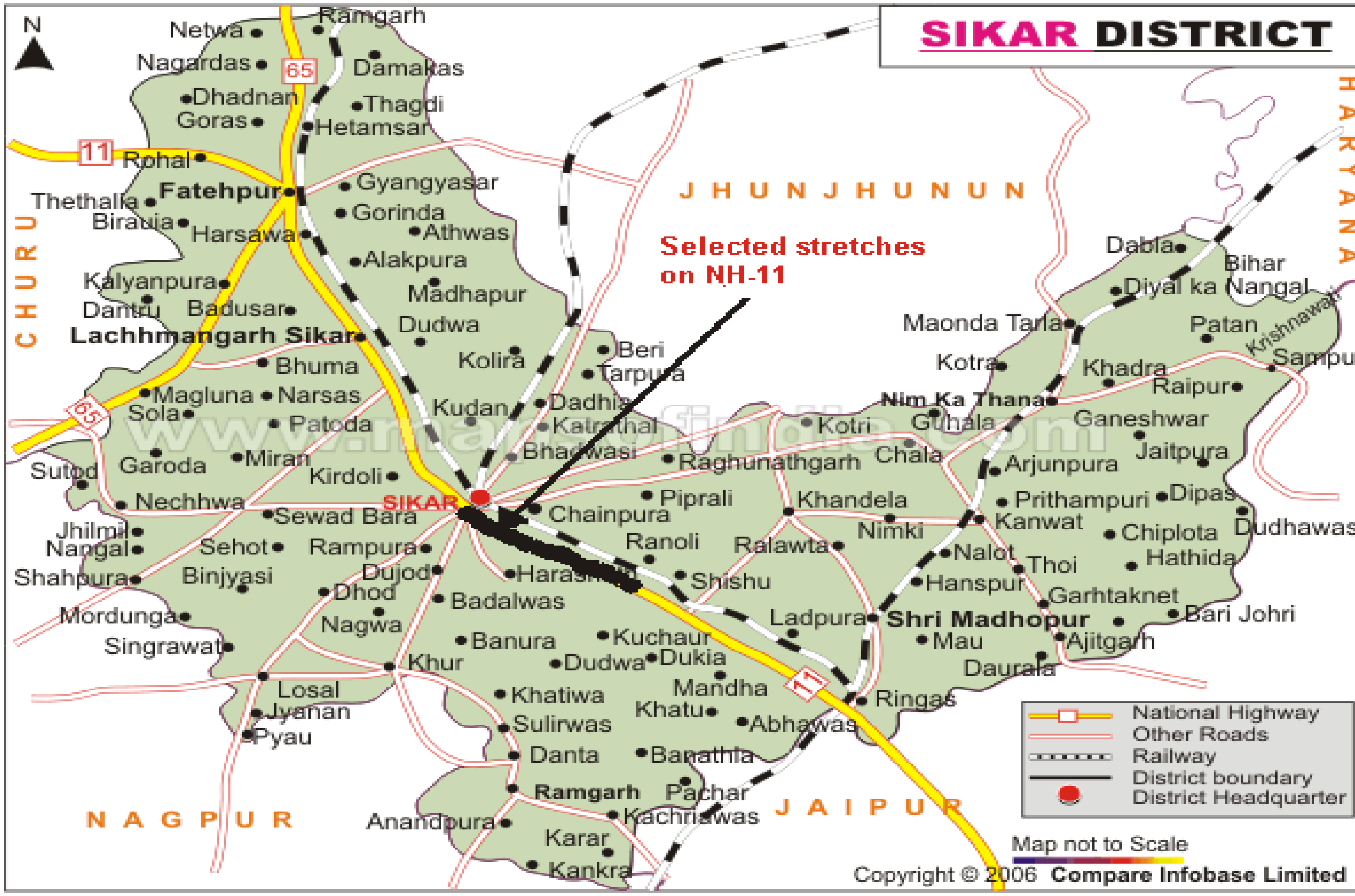


Fig 4.1: Selected stretches on National Highway-11 in Sikar district of Rajasthan

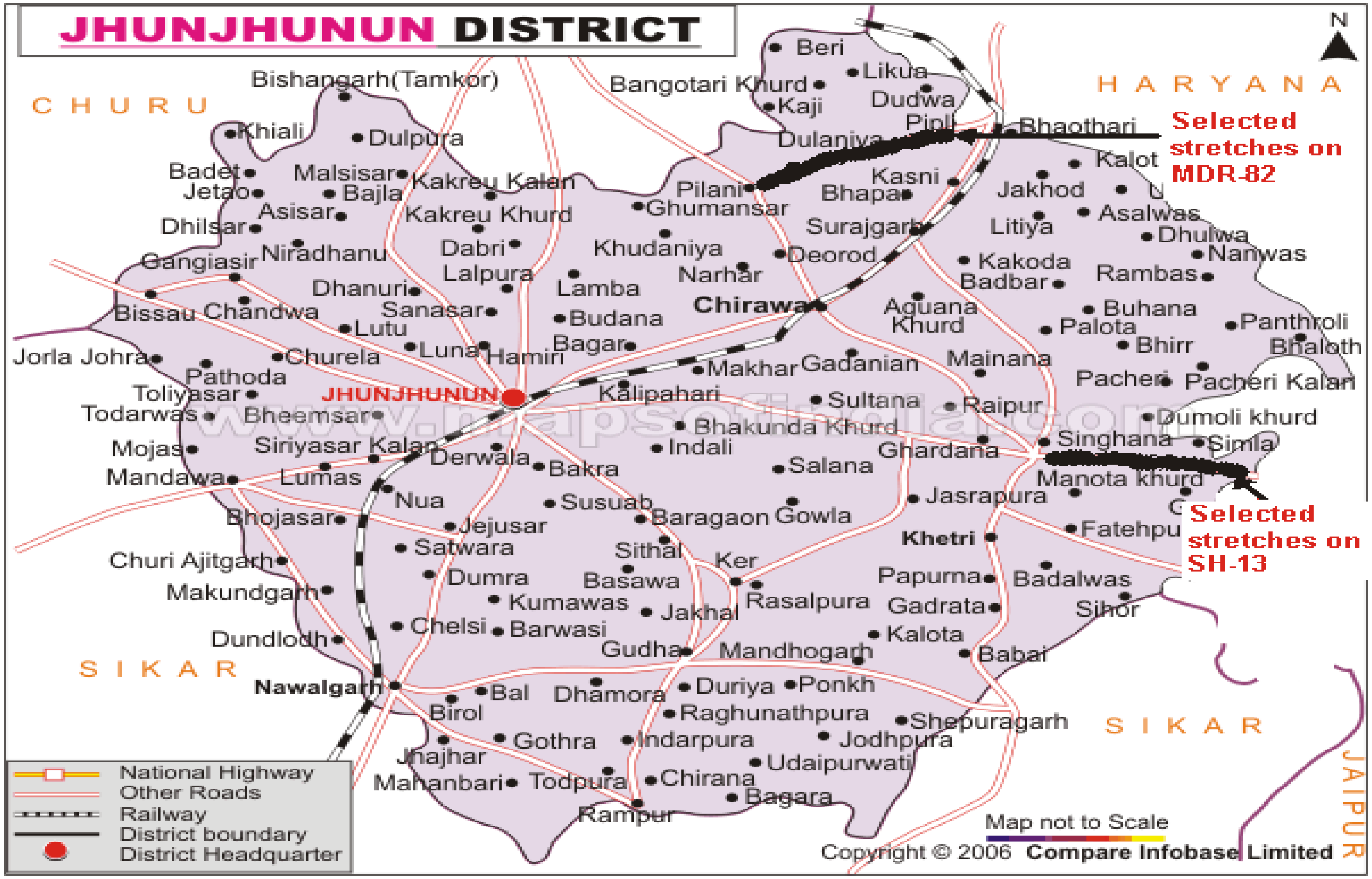


Fig 4.2: Selected stretches on State Highway-13 and Major District Road-82 in Jhunjhunu district of Rajasthan

researchers (Miller and William, 2003; NCHRP, 2004; Naidu, 2005, IRC: 82, 1982). For example, it may be observed that the severity of cracking has been considered as low if width is less than 3 mm, it is medium when it is between 3 mm and 6 mm and high when width is more than 6 mm. Similarly, the severity levels of other distresses have been clearly defined in the Table 4.2.

4.2.3 Pavement Marking for Data Collection along the Wheel Path

The selected test stretches were divided into uniform sections of length 50 m each. Possibilities of distresses are more along the wheel path and thus the wheel path was identified by visual observation and bands of 24 cm width were marked in the longitudinal direction covering the entire section length. The width of 24 cm was arrived at by considering the 12 cm Bump Integrator wheel width with extra 12 cm leverage for it to wander along either side of the path. A typical photograph displaying marking scheme is shown in Plate 4.1.

4.2.4 Enumerators Training

As a prerequisite for conducting the study, chosen set of enumerators were trained in the class room on the collection of pavement distress data by visual observation with the aid of description of pavement distress severity levels presented in Table 4.2 and also on how to measure extent of each parameter. They were also trained in the field to ensure the accuracy and uniformity in the data collection process. Provision was made to verify the data collected by the enumerators to ensure the quality and accuracy. In addition, a simple distress identification procedure developed with photographic clues and cues as shown in *Appendix 1* has also been supplied to these enumerators as an aid during the data collection process.

Table 4.2: Description of Flexible Pavement Distress Severity Levels

S.No	Type of Distress	Severity	Description
1	Cracking	Low	Width of the cracking is less than 3mm
		Medium	Width of the cracking is greater than 3mm and less than 6mm
		High	Width of the cracking is greater than 6mm
2	Potholes	Low	Depth of the pothole is less than 25mm
		Medium	Depth of the pothole is more than 25 mm and less than 50 mm
		High	Depth of the pothole is more than 50 mm
3	Raveling	Low	The aggregate or binder has started to wear away but has not progressed significantly. The pavement appears only slightly aged and s lightly rough.
		Medium	The aggregate or binder has worn away and the surface texture is moderately rough and pitted. Loose particles may be present and fine aggregate is partially missing.
		High	The aggregate and/or binder have worn away significantly, and the surface texture is deeply pitted and very rough. Fine aggregate is essentially missing from the surface, and pitting extends to a depth approaching one half (or more) of the coarse aggregate size.
4	Patching	Low	Patch has low severity distress of any type including rutting < 6 mm; pumping is not evident
		Medium	Patch has moderate severity distress of any type or rutting from 6 mm to 12 mm; pumping is not evident.
		High	Patch has high severity distress of any type including rutting > 12 mm, or the patch has additional different patch material within it; pumping may be evident.
5	Rutting	Low	Barely noticeable, depth less than 6 mm
		Medium	Readily noticeable, depth more than 6 mm less than 25 mm
		High	Definite effect upon vehicle control, depth greater than 25 mm
6	Edge Failure	Low	Appearance of edge step with a few initial cracks on the bituminous surface along the edge portion of the carriageway
		Medium	Appearance of edge step with a number of interconnected high intensity cracks on the bituminous surface along the edge portion of the carriageway
		High	Permanent loss of part of carriageway and pothole formation along the edge portion

Plate 4.1: Marking along the Wheel Path

4.2.5 Preparation of Proforma

Two separate proforma were developed for collecting the pavement condition data. One was for collection of data along the wheel path and other one for collection over the entire width of the pavement (*Appendix 2*). Special care was taken to make the proforma as simple as possible so that enumerators would not face any difficulty in the filed.

4.2.6 Pavement Condition Survey

Pavement condition data along the marked wheel path and entire width of the pavement was collected separately. Extent of pavement distress parameters such as cracking, potholes, patching, raveling and edge failure expressed in three severity levels were measured in terms of area in square meter by encompassing distresses area with in a regular geometric shape such as square, rectangle and triangle. The extent of rutting was measured in length in meters along the longitudinal direction. The detailed methods of measuring the severity of distresses are discussed in the following section.

4.2.6.1 Cracking

To identify the severity of cracks, width of the cracks were measured in mm. It was done by inserting a suitable gauge of known thickness into the crack. Cracks were classified in three severity levels namely low, medium and high on the basis of width as shown in Table 4.2. The area of the cracks in square meter of each severity were measured separately. In a particular area if cracks of different widths were observed, those were recorded separately.

4.2.6.2 Potholes

The severity of potholes was classified based on its depth as presented in Table 4.2. A straight edge of length 3 m was placed over the potholes and then highest depth was measured by inserting a metric scale into the pothole. After identifying the severity, the area of the pothole was measured in m^2.

4.2.6.3 Patching

Severity of patching was identified by observing the condition of the patching visually and with the help of description given in Table 4.2. Rutting if any found over the patched area was also measured using 3 m straight edge and was taken into consideration while deciding the severity of patching.

4.2.6.4 Raveling

With the help of the description given in Table 4.2 and using photographic clues and cues the severity levels of raveling were decided and the area of raveling of all severities were measured in square meter.

4.2.6.5 Rutting

Depth of the rutting was measured by placing the 3 m long straight edge across the road and inserting a wedge scale under the straight edge. Based on the depth of the rutting, it was classified into three severity levels as discussed in Table 4.2. The length of the rutting of was expressed in meter.

4.2.6.6 Edge failure

Using photographic clues and cues and with the help of description given in Table 4.2, the severity levels of edge failure was identified. The extent of edge failure was measured in terms of area (square meter) by multiplying the length and maximum width of the edge break. Width of the edge break has been calculated by deducting the effective width of the pavement available after the edge break from the actual width of the pavement.

4.2.6.7 Pavement roughness

Using Towed Fifth wheel Bump Integrator, roughness data was recorded along the marked wheel path for a section of 50 m length. The roughness /Unevenness Index (UI) obtained from the Bump Integrator was in mm/km. Towed Fifth wheel Bump Integrator Model-V used in the present study has the inbuilt facility to convert the roughness into the standard measurement of mm/km irrespective of the distance covered. To ensure that the UI values taken on 50 m sections were acceptable a stretch of length 1km is chosen and UI values was found for the stretch. Then the same stretch was divided into 20 sections and UI values were recorded for each section separately. It was observed that the average of the UI values collected on 20 sections was almost equal to the UI value obtained for the stretch. Bump Integrator was calibrated and standardized before collection of the roughness data. The data collected for calibration and standardization has been discussed in sections 4.3 and 4.4.

Pavement condition and roughness data collected along the wheel path and entire width of the pavement were stored in a format as presented in Table 4.3 and Table 4.4 respectively. The tables show sample data of 20 sections collected over 1 km stretch. It is to be noted here that the distresses along the wheel path measured over width of 24 cm. It may be observed from the table that, while collecting the data along the wheel path all the distress parameters except for edge failures were considered for obvious reasons.

Table 4.3: Sample data Collected along the Wheel Path

S.No	Unevenness Index (mm/km)	Criteria														
		CL	CM	CH	PL	PM	PH	RL	RM	RH	PAL	PAM	PAH	RUL	RUM	RUH
1	4955	1.68	1.44	0.89	6.14	1.08	0.00	0.77	0.00	0.00	0.00	0.00	0.00	11.00	0.00	0.00
2	4982	1.44	4.92	3.84	1.20	0.60	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	8.00	0.00
3	4882	3.36	2.33	0.00	5.83	0.00	0.00	0.32	0.16	0.00	0.00	0.00	0.00	0.00	8.00	0.00
4	4791	0.96	1.00	0.00	5.42	1.20	0.00	0.18	0.00	0.12	3.12	0.00	0.00	0.00	0.00	0.00
5	5863	0.00	0.00	3.12	5.04	2.30	1.46	0.06	0.00	0.01	0.00	0.00	0.00	0.00	4.00	0.00
6	6045	0.00	0.00	6.36	0.00	3.65	1.03	0.38	0.00	0.58	0.00	0.00	0.00	0.00	0.00	0.00
7	6308	0.00	1.46	7.68	0.00	1.01	1.54	0.17	0.00	0.14	0.00	0.00	0.00	27.00	0.00	0.00
8	6990	3.00	1.80	1.58	1.10	1.30	2.16	0.34	0.50	0.22	0.00	0.00	0.00	20.00	12.00	5.00
9	6399	0.00	1.63	2.47	0.00	3.22	4.22	0.10	0.16	0.19	0.00	0.00	0.00	17.00	0.00	0.00
10	6017	0.99	0.00	1.97	1.97	1.51	2.98	0.07	0.00	0.13	0.00	1.27	1.10	10.00	8.00	3.00
11	5963	0.00	0.00	3.26	1.21	2.96	0.58	0.62	0.20	0.14	0.00	3.02	0.00	22.00	0.00	0.00
12	6017	0.00	1.52	2.78	0.00	1.54	2.06	0.18	0.00	0.22	0.00	3.70	0.00	18.40	5.00	0.00
13	5651	0.00	0.00	5.40	5.40	0.55	0.00	0.08	0.16	0.00	0.00	0.41	0.00	14.00	0.00	0.00
14	3628	10.44	1.56	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	15.00	0.00	0.00
15	3991	10.61	1.39	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	20.00	0.00	0.00
16	3827	10.94	1.06	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	14.00	6.00
17	3464	10.58	1.42	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
18	3409	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
19	3328	12.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00
20	4255	6.05	1.34	0.00	4.61	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

LEGEND:

CL=Low level cracking in m^2 CM=Medium level cracking in m^2 CH =High level cracking in m^2

PL=Low level potholes in m^2 PM=Medium level pothole in m^2 PH =High level potholes in m^2

RL=Low level raveling in m^2 RM=Medium level raveling in m^2 RH=High level raveling in m^2

PAL=Low level patching in m^2 PAM=Medium level patching in m^2 PAH=High level patching in m^2

RUL=Low level rutting in m RUM=Medium level rutting in m RUH=High level rutting in m

Table 4.4: Sample Data Collected on the Entire Width of the Pavement

S.No	Criteria																	
	CL	CM	CH	PL	PM	PH	RL	RM	RH	PAL	PAM	PAH	RUL	RUM	RUH	EL	EM	EH
1	0.00	0.00	0.00	0.60	0.88	0.00	2.47	10.01	44.81	3.20	26.91	10.10	4.7	0.0	0.0	0.78	0.00	0.00
2	0.00	0.00	0.00	0.27	1.05	0.00	36.07	31.07	4.05	11.18	15.64	0.00	0.0	6.8	0.0	0.63	0.00	0.00
3	1.71	0.00	0.00	1.47	0.14	0.00	54.00	20.00	1.43	0.00	3.43	1.71	0.0	0.0	0.0	0.00	0.00	0.00
4	26.00	0.00	0.00	0.31	0.00	0.00	50.00	10.00	0.00	0.00	0.00	0.00	8.4	0.0	9.0	0.29	0.00	0.00
5	2.00	2.00	0.00	0.71	0.71	0.21	56.00	10.00	26.00	0.00	1.71	0.00	9.4	8.1	0.0	0.57	0.00	0.00
6	18.00	14.00	0.00	0.50	0.06	0.00	48.00	18.00	0.00	0.00	0.00	0.00	7.5	0.0	0.0	0.17	0.00	0.00
7	0.00	0.00	0.00	0.29	2.14	0.35	20.00	50.00	18.00	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.00
8	0.00	0.00	0.00	0.14	0.21	1.33	0.00	20.21	28.87	0.00	11.43	0.00	16.9	8.1	9.0	1.71	0.00	0.00
9	0.00	0.00	0.00	0.00	0.00	1.91	0.00	48.00	26.00	0.00	18.00	0.00	20.6	10.8	5.0	0.20	0.00	0.00
10	0.00	0.00	0.00	0.29	0.86	1.86	0.00	24.57	54.00	0.00	0.06	4.00	0.0	0.0	0.0	0.00	0.00	0.00
11	0.00	0.00	0.00	10.29	30.63	8.14	0.00	43.14	0.00	0.00	3.00	0.00	11.3	0.0	0.0	0.00	0.00	0.00
12	0.00	0.00	0.00	0.34	1.42	1.08	2.00	0.00	38.00	6.00	24.86	15.00	0.0	0.0	0.0	0.00	0.00	0.00
13	0.00	0.00	0.00	2.52	11.86	1.66	0.00	12.29	32.00	0.00	0.86	0.00	22.5	11.5	8.0	0.00	1.26	1.00
14	0.00	0.00	0.00	0.86	2.77	3.21	0.00	58.00	8.00	0.00	4.00	0.00	0.0	0.0	0.0	0.43	0.51	0.00
15	0.00	0.00	0.00	0.17	1.34	5.05	14.00	14.00	37.14	20.00	0.00	0.00	9.4	0.0	0.0	0.46	0.00	1.37
16	0.00	0.00	0.00	0.26	0.79	3.63	30.00	22.00	14.00	18.00	0.00	0.00	15.0	4.1	2.0	0.57	1.71	0.00
17	2.00	0.00	0.00	0.43	0.00	0.00	96.00	0.00	0.00	0.00	0.00	0.00	0.0	0.0	0.0	0.00	0.00	0.00
18	0.00	0.00	0.00	0.09	0.73	1.76	70.00	16.14	6.14	0.00	0.00	0.00	12.2	3.4	4.0	0.00	0.00	0.00
19	4.00	0.00	0.00	0.31	0.14	0.00	86.17	0.00	0.00	0.00	6.00	0.00	0.0	0.0	0.0	0.00	0.00	0.00
20	4.00	0.00	0.00	0.57	0.71	0.00	68.00	9.00	0.00	0.14	14.21	0.00	19.7	0.0	0.0	0.00	0.00	0.00

LEGEND:

CL=Low level cracking in m^2 CM=Medium level cracking in m^2 CH =High level cracking in m^2

PL=Low level potholes in m^2 PM=Medium level pothole in m^2 PH =High level potholes in m^2

RL=Low level raveling in m^2 RM=Medium level raveling in m^2 RH=High level raveling in m^2

PAL=Low level patching in m^2 PAM=Medium level patching in m^2 PAH=High level patching in m^2

RUL=Low level rutting in m RUM=Medium level rutting in m RUH=High level rutting in m

EL=Low level edge failure in m^2 EM=Medium level edge failure in m^2 EH=High level edge failure in m^2

4.3 DATA COLLECTION FOR CALIBRATION OF BUMP INTEGRATOR USING MERLIN

Fifth wheel Bump Integrator used in the present study was calibrated with MERLIN (Machine for Evaluating Roughness using Low-cost INstrumentation). Pavement roughness was measured with both the equipment on six specially selected stretches of road for calibration.

4.3.1 Selection of the Calibrated Sections

The following criteria were followed while selecting the sections for calibration (Bennet, 1996; Sayers et al., 1986; Cundill, 1991)

- The sections of length 225 m selected by ensuring that they were on straight stretches having at least another 100 m length of straight alignment before and after the selected section
- The roughness on the selected sections was fairly uniform over the entire length
- The surface of the pavement was in fair condition without any potholes or depressions
- All the selected pavement sections were machine laid asphalt concrete surface

4.3.2 Roughness Data Collection using MERLIN and Bump Integrator

Kampax (1992) and Bennet (1996) have recommended the calibration of MERLIN on a standard floor before being used for either calibrating the Bump Integrator or for finding the roughness itself. Accordingly, the calibration process was carried out on a flat unyielding surface inside the laboratory. They were also suggested equation for finding the correction factor for the 10:1 (1 mm vertical movement of the probe will produce a pointer movement of 1 cm.) MERLIN as given in Eq 4.1.

$$CF = (10*T) / PM_p \quad (4.1)$$

Where

CF = MERLIN correction factor,

T = thickness of the plate (mm), and

PM_p = movement of the pointer (mm).

To find the correction factor, five different gauges were chosen and thicknesses of the gauges were measured accurately using vernier calipers. These gauges were inserted under the probe of the MERLIN and movement of the pointer was measured. The average correction factor was calculated by taking the average of all the five correction factor obtained using different thickness gauges. This detail has been presented in Table 4.5. Calibration of MERLIN on the floor has been shown in Plate 4.2.

Table 4.5: Calculation of MERLIN Correction Factor

S.No	Thickness of Gauge (mm)	Movement of MERLIN Pointer (mm)	Correction Factor using Eq. 4.1	Average Correction Factor
1	1.5	16	0.94	0.94
2	3	33	0.91	
3	4.2	44	0.95	
4	5	53	0.94	
5	6.2	65	0.95	

On the selected 6 stretches, marking was done with chalk over entire length of the stretches. Roughness on a section of road was collected by wheeling the MERLIN along the road with the handles raised. As per IRC: SP: 16-2004 procedure, at least 200 measurements are to be made with MERLIN at regular intervals to produce a histogram. The perimeter of the tyre in the MERLIN equipments is 2.25 m, hence, for every half revolution one measurement was made over the length of 225 m. After every half wheel revolution, the handle was lowered so that the probe and rear foot touch the ground; the resulting pointer position is recorded as a cross on a chart.

Plate 4.2: Calibration of MERLIN on the Floor

After completion of the survey, the chart was removed and width of the 90 percent of histogram was measured. This is done by deleting 5% of extreme points on both the sides of histogram. Sample of one MERLIN histogram is shown in Fig 4.3. Further, the MERLIN D-value is being calculated by multiplying the width of the resulting histogram with the correction factor established during the calibration phase.

On the same sections and on marked path roughness values were measured using Bump Integrator running at 32km/hr speed. On one calibrated section, roughness was measured 5 times and average value was taken for calibration. Roughness values obtained from each run of the Bump Integrator and corresponding MERLIN D-value on different sections have been presented in

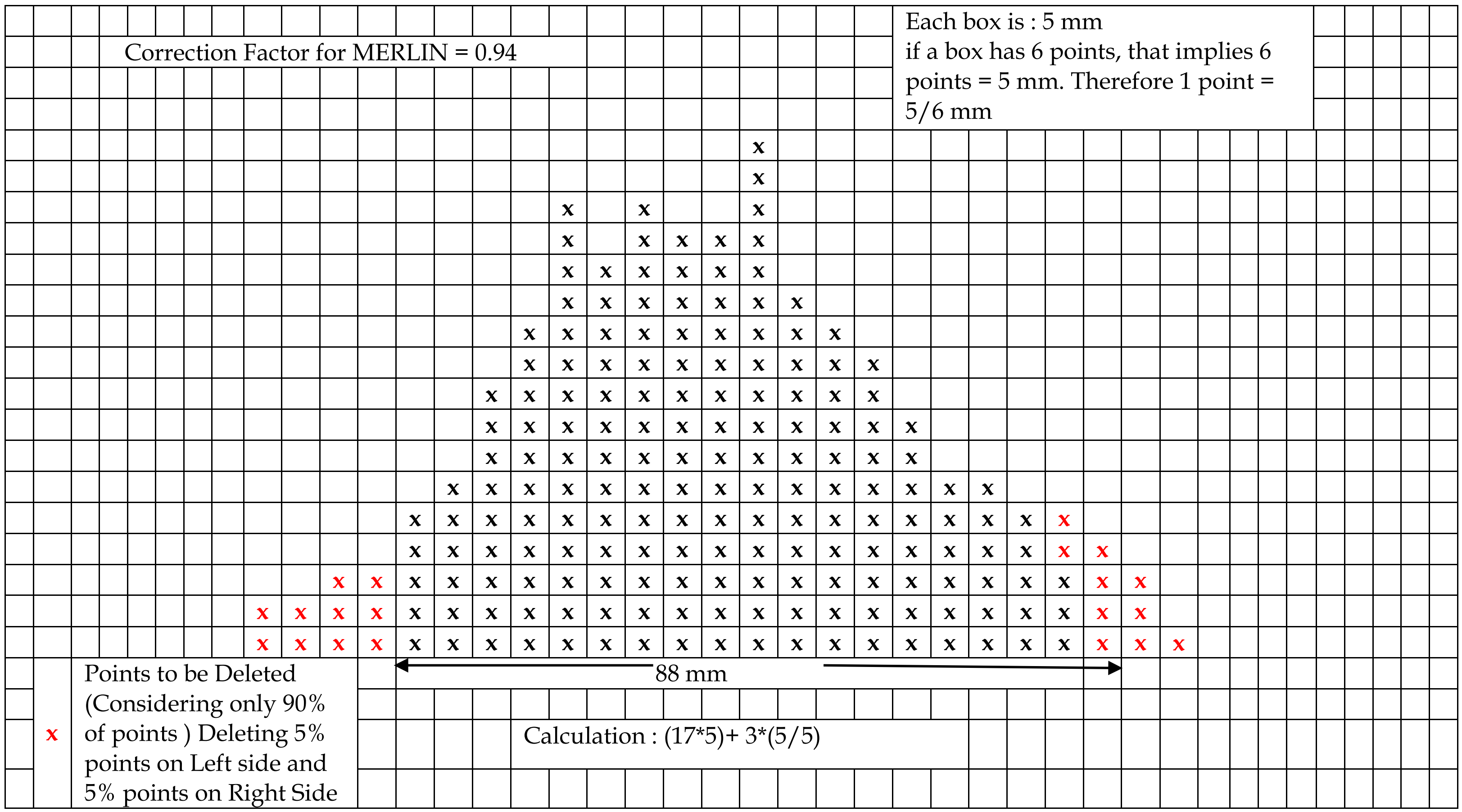


Fig 4.3: Histogram for Measuring Roughness using MERLIN

Table 4.6. It can be observed that, the MERLIN D-values and the roughness values obtained from the Bump Integrator are directly proportional to each other. In addition, on the selected stretches MERLIN D- values varies from 64.7 to 95.2 and Bump Integrator roughness values varies from 2516 mm/km to 3445 mm/km.

Table 4.6: MERLIN and Bump Integrator Values on Selected Test Sections

Stretch No.	Length	MERLIN D-Value	Unevenness Index (UI) value in mm/km					Average Unevenness Index value
			RUN 1	RUN 2	RUN 3	RUN 4	RUN 5	
1	225	82.5	3082	3131	3058	3074	3071	3083
2	225	86.7	3147	3163	3179	3131	3115	3147
3	225	88.6	3227	3301	3261	3293	3276	3271
4	225	95.2	3373	3421	3518	3470	3445	3445
5	225	64.7	2488	2534	2496	2542	2522	2516
6	225	65.6	2586	2612	2592	2632	2652	2614

4.4 DATA COLLECTION FOR STANDARDIZING THE UNEVENNESS INDEX AT DIFFERENT OPERATING SPEEDS

It has been already discussed in section 4.1 that it was difficult to maintain the standard speed of 32km/hr on a number of stretches due to poor road conditions and heterogeneous traffic. Thus it was felt necessary to develop a relationship between the roughness observed at 32km/hr and those of at other speeds separately. Accordingly, roughness surveys at different operating speeds were carried out on some of the selected road sections. The details of this survey are being presented in the following sections.

4.4.1 Selection of Stretches

For the collection of data, different stretches having a wide variation in roughness values were identified. For this purpose, roughness values were measured using Bump Integrator running at 32km/hr speed along the wheel path covering different stretches of National Highways (NHs), State Highways (SHs) and Major District Roads (MDRs) passing through Jhunjhunu and Sikar districts of Rajasthan. After a careful study, a total of 37 stretches having wide range of roughness values were selected.

For uniformity, while selecting the stretches, care was taken to ensure that they were on the straight portion of the alignment as to avoid the effect of road geometrics. In addition, the locations were chosen to avoid local traffic interferences by selecting them fairly away from the cities, villages and intersections. It was also ensured that the pavement condition in a particular stretch was more or less uniform and length of the each stretch was 1 km. The details of the selected stretches for the study are shown in Table 4.7. It may be observed that out of 37 stretches 7 were on NHs, 16 on SHs and 14 on MDRs.

Table 4.7: Details of the Stretches

S.No	Stretch No.	Name of the Road	Class of the Road	Chainage (km)		Length (km)
				From	To	
1	1-4	Sikar - Jaipur	NH -11	11	15	4
2	5-7	Reengas - Sikar	NH -11	38	41	3
3	8-11	Jhunjhunu - Loharu	SH - 8	34	38	4
4	12-15	Loharu – Jhunjhunu	SH – 8	19	23	4
5	16	Jhunjhunu - Loharu	SH - 8	29	30	1
6	17	Loharu – Jhunjhunu	SH – 8	28	29	1
7	18-21	Pilani - Loharu	MDR-82	2/550	6/550	4
8	22-25	Loharu - Pilani	MDR-82	16/400	20/400	4
9	26-28	Pilani - Loharu	MDR-82	12	15	3
10	29-31	Loharu - Pilani	MDR-82	10	13	3
11	32-34	Singhana - Narnoul	SH-13	9	12	3
12	35-37	Pachori - Singhana	SH-13	0	3	3
					Total Length(km)	**37**

The roughness values obtained by conducting Bump Integrator survey carried out at a speed of 32 km/hr on the selected stretches varied between 2300 mm and 5000 mm per km. As per Indian Road Congress (IRC) specifications, bituminous concrete pavement surfaces were classified as good for roughness values ranging between 2000-2500 mm/km, average for the values between 2500-3500 mm/km, poor for between 3500-4000 mm/km and very poor for the values greater than 4500 mm/km (IRC: SP-30, 1993). All the selected stretches in the present study were bituminous surfaces and hence it was decided to consider the pavement stretches with roughness values less than 2500 mm/km as even and rest are as uneven surfaces. Out of the 37 selected stretches 25 were observed to be uneven while the remaining 12 had even surfaces.

4.4.2 Bump Integrator Studies at different Running Speeds

The selected stretches were marked along the identified wheel paths (left and right paths separately) as discussed in section 4.2.3. Bump Integrator surveys were conducted on all the marked stretches with different operating speeds ranging from 10-50 km/hr at a uniform increment of 5 km/hr. To minimize errors the survey was conducted twice on the same stretch and the average was considered for the analysis. In addition, the Bump Integrator surveys were also conducted at the standard calibrated running speed of 32 km/hr. While conducting the Bump Integrator survey, continuous monitoring was done to ensure that the fifth wheel was being placed within the marked wheel path band. A photograph showing this data collection process is presented in Plate 4.3.

The summary of data collected at different speeds on 20 selected uneven and 12 selected even surfaces are presented in Table 4.8 and Table 4.9 respectively. Data collected on the remaining five uneven stretches shown in

Table 4.10 were kept aside for validation purpose. It can be observed from the Table 4.8 and Table 4.9 that, on the uneven surfaces the roughness values on particular section of the pavement are decreasing with increasing running speed and on the even surfaces the roughness values on a particular section of the pavement are not following any trend with increasing running speed.

Plate 4.3: Bump Integrator Survey

Table 4.8: Unevenness Index Data Collected on Uneven Surfaces at different Operating Speeds

Stretch No.	Unevenness Index at 32km/hr	Unevenness Index (mm/km) at different speeds (km/hr)								
		10	15	20	25	30	35	40	45	50
1	2770	3395	3139	3098	3031	2835	2719	2600	2510	2302
2	2902	3475	3431	3249	3155	2966	2884	2806	2748	2515
3	3144	3522	3436	3426	3277	3200	3075	3010	2922	2879
4	3451	3947	3675	3567	3564	3489	3346	3293	3120	3090
5	3500	3967	3738	3656	3600	3531	3400	3309	3171	2975
6	3522	3987	3758	3676	3635	3551	3420	3329	3191	2995
7	3727	4362	4289	4118	4058	3817	3657	3569	3329	3148

Stretch No.	Unevenness Index at 32km/hr	Unevenness Index (mm/km) at different speeds (km/hr)								
		10	15	20	25	30	35	40	45	50
8	**3820**	4564	4343	4309	4165	3962	3773	3629	3500	3344
9	3860	4665	4465	4402	4226	3998	3800	3671	3540	3402
10	3880	4672	4493	4565	4238	4040	3820	3649	3569	3395
11	4258	5607	5281	5220	4671	4380	4170	3969	3729	3562
12	4320	5661	5394	5291	4774	4427	4222	3926	3786	3584
13	4350	5712	5529	5350	4805	4447	4260	4035	3831	3693
14	4394	5898	5592	5452	4871	4480	4298	3969	3889	3686
15	4485	6023	5673	5481	4936	4589	4382	4049	3904	3693
16	4678	6354	6143	5709	5212	4685	4471	4173	4093	3853
17	4769	6425	6236	5990	5271	4800	4638	4398	4129	3940
18	4914	6610	6419	6128	5485	5092	4714	4541	4269	4153
19	4925	6650	6445	6197	5514	5136	4740	4564	4296	4191
20	4930	6783	6472	6235	5583	5172	4718	4580	4325	4280

Table 4.9: Unevenness Index Data Collected on Even Surfaces at different Operating Speeds

Stretch No.	Uneven-ness Index At 32km/hr	Unevenness Index (mm/km) at different speeds (km/hr)								
		10	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**
1	2288	2399	2121	2677	2326	2355	2266	2316	2341	2283
2	2346	2304	2123	2635	2399	2442	2473	2295	2355	2297
3	2362	2473	2279	2664	2413	2428	2326	2283	2428	2326
4	2368	2457	2266	2635	2355	2368	2210	2239	2326	2283
5	2382	2472	2266	2590	2384	2341	2326	2239	2428	2297
6	2386	2253	2094	2508	2457	2442	2326	2341	2486	2355
7	2386	2430	2308	2606	2399	2399	2381	2283	2370	2224
8	2388	2048	2123	2666	2486	2457	2326	2268	2413	2326
9	2400	2152	2164	2550	2428	2472	2355	2268	2256	2370
10	2410	2404	2381	2608	2544	2486	2370	2312	2486	2413
11	2420	2166	2094	2580	2428	2472	2326	2253	2164	2413
12	2431	2121	2123	2322	2530	2457	2370	2341	2457	2413

Table 4.10: Unevenness Index Data Collected on Uneven Surfaces at different Operating Speeds for Validation Purpose

Stretch No.	Unevenness Index at 32km/hr	Unevenness Index (mm/km) at different speeds (km/hr)								
		10	15	20	25	30	35	40	45	50
1	2810	3302	3182	3118	3062	2862	2732	2624	2526	2443
2	3782	4586	4342	4192	4096	3932	3714	3612	3422	3212
3	4318	5607	5281	5220	4671	4380	4170	3969	3729	3562
4	4920	6528	6252	5800	5418	5096	4740	4573	4370	4229
5	5010	6868	6506	5997	5552	5278	4913	4638	4505	4424

4.5 ROUGHNESS DATA OVER ENTIRE WIDTH OF THE PAVEMENT

To develop the relationships between pavement roughness and distress parameters, data was collected along the marked wheel path as discussed in section 4.2. However, it is a general practice to collect the pavement distress parameters over the entire width of the pavement. Thus to validate the developed relationship, the roughness and the distress parameters were collected over a number of strips on the entire width of pavement. For this study, data was collected on MDR, SH and NH. One lane of one km length was chosen on each kind of road. This 1 km stretch was subdivided into 20 uniform sections of 50 m length. Details of the selected stretches are given in Table 4.11.

The lane width of 3.5 m was subdivided into 14 equal strips of 24 cm (width of 24 cm is arrived at by considering the 12 cm Bump Integrator wheel width with extra 12 cm leverage for it to accommodate the wheel wander along either side of the wheel path of the fifth wheel of the Bump Integrator) each marked with paint. Keeping in view the difficulty in running the Bump Integrator, 10 cm from the edge of the pavement was left out. A photograph showing the paint marks is presented in plate 4.4.

Table 4.11: Details of the Selected Stretches for Collecting Roughness and Distress Data over Entire Width of the Pavement

Functional Class of Highway	Name of the Road	Lane	Chainage (km)		No. of sections
			From	To	
MDR	Pilani - Loharu	Left	3	4	20
SH	Singhana - Narnoul	Left	15	16	20
NH	Sikar - Jaipur	Left	13	14	20

Plate 4.4: Marking Over Entire Width of the Pavement

Bump Integrator was run with test wheel being placed successively on all the marked strips and roughness values were found. Then the average roughness value over the entire lane was calculated from the roughness obtained from all the fourteen strips. Pavement distress parameters were also simultaneously collected on the same sections over the entire width. Summary of roughness data collected over MDR of 1 km length has been presented in Table 4.12 as a sample. It is to be noted here that the roughness data presented in the Table 4.12 over entire width of the pavement was collected on the same stretch as presented in Table 4.4.

4.6 DATA COLLECTION THROUGH EXPERT OPINION SURVEYS

One of the primary objectives of the present study is to develop the methodology for pavement maintenance. Decisions for maintenance activities are generally being taken based on the functional condition of the pavement. Distress parameters which affect the condition of the pavement might not have same impact; hence, an expert opinion survey was conducted to ascertain the weights of the pavement distress parameters. The questionnaire shown in *Appendix 3* was developed and sent to number of experts with academic background and field experiences. Cues and clues in the form of photographs and explanations as shown in *Appendix 1* were also sent to these experts to help them and also to ensure uniformity in their views. Weights of pavement distress parameters are subjective in nature and it would be difficult to express them in quantifiable terms, and thus, the experts were asked to rate the weights in terms linguistic variables such as Negligible (N), Low (L), Moderate (M), High (H) and Very High (VH). Questionnaires were sent to 30 selected experts across India and 20 of them responded. Opinions of 20 experts are presented in Table 4.13.

Table 4.12: Sample of Unevenness Index Data Collected on Different Wheel Paths over Entire Width of the Pavement on Major District Road

Section No.	Unevenness Index (mm/km) collected on different wheel paths														Average UI (mm/km)
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	
1	4926	5318	5012	4729	5012	4926	4729	4833	5096	4729	4729	4827	4853	4729	**4889**
2	5318	6497	6578	6479	6301	5827	5915	6301	6497	6006	5918	5690	5810	5918	**6075**
3	5814	5915	6479	6890	6497	5908	6399	6301	5712	5712	5617	5635	5632	5417	**5995**
4	4926	5515	6105	6596	6392	6596	6185	6203	6381	6485	6301	6327	6280	6301	**6185**
5	5632	6010	5815	5617	5715	5421	6006	5890	5988	6006	5908	5677	5732	5908	**5802**
6	7185	6988	7069	6987	6988	6114	6788	6790	6478	6399	6406	6887	6399	6406	**6706**
7	6301	6792	7064	6872	7078	6596	6988	6694	6792	6694	6601	6565	6506	6601	**6725**
8	6694	7087	7078	6992	6896	6799	6899	6906	6890	6890	6839	6352	6294	6439	**6790**
9	7234	7108	7128	6792	6596	6399	6399	6006	6870	6860	6749	6422	6439	6749	**6697**
10	5712	6890	6287	6688	6583	5817	6203	6497	5515	5417	5632	5615	5435	5532	**5987**
11	6890	7185	7381	7381	6596	5417	5614	5614	6087	6006	5712	6205	5318	5712	**6223**
12	6890	6399	6988	7087	6105	5712	5417	6203	5123	5123	5123	5317	5318	5423	**5873**
13	5318	6694	6301	6203	5614	5318	5417	5221	6301	5908	5417	6271	5832	5617	**5817**
14	3845	5221	5318	4926	5024	4747	3944	5515	4533	4533	4435	5004	5024	4435	**4750**
15	3845	4238	4326	4238	3747	3747	3845	4926	4632	4042	3944	3925	3788	3824	**4076**
16	3649	3453	4454	4533	4632	4238	4042	4435	3845	4435	4140	4353	3956	4040	**4158**
17	3645	3744	3744	3560	3458	3667	3551	3560	4336	3944	3453	3421	3951	3453	**3678**
18	3453	3354	4140	3962	3863	3758	3858	3453	3649	4140	4336	3725	4142	4336	**3869**
19	3845	4729	4729	4435	4435	3747	4336	3256	4632	3944	4042	4018	4042	4142	**4167**
20	4435	5318	4626	4221	4332	3845	3845	4435	4238	3944	4042	4233	4533	4042	**4292**

Table 4.13: Summary of Experts Opinions

Criteria	Experts																			
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20
(CL)	L	N	N	L	N	N	N	N	N	N	L	L	N	L	N	L	N	L	L	L
(CM)	M	M	L	M	N	L	L	L	L	L	M	M	L	M	L	M	M	M	M	M
(CH)	H	H	M	H	L	M	M	VH	L	M	H	H	M	H	M	H	H	VH	H	H
(PL)	M	L	L	M	N	M	M	M	M	M	M	L	L	L	M	M	M	L	M	M
(PM)	H	H	M	H	L	H	H	H	H	H	H	M	M	M	H	H	H	M	H	H
(PH)	VH	VH	H	VH	H	VH	VH	VH	VH	VH	VH	VH	H	H	VH	VH	VH	VH	VH	VH
(RL)	M	L	L	N	N	M	L	L	L	L	N	N	N	N	N	M	L	N	N	N
(RM)	H	M	M	L	N	H	M	M	L	M	L	L	L	L	N	H	M	L	L	L
(RH)	VH	H	H	M	M	VH	VH	H	M	H	M	H	M	H	M	VH	VH	H	M	H
(PAL)	L	N	L	N	N	M	N	N	M	M	N	N	L	L	L	L	N	N	N	L
(PAM)	M	M	M	L	L	H	L	M	M	H	L	L	M	M	M	M	L	L	L	M
(PAH)	H	H	H	M	M	VH	M	VH	H	VH	M	M	M	H	H	H	M	M	H	H
(RUL)	M	N	L	N	L	L	N	N	L	L	L	N	L	N	L	L	N	N	L	N
(RUM)	H	M	L	L	M	M	L	L	M	M	M	L	M	M	M	M	L	L	M	L
(RUH)	VH	VH	M	M	VH	H	M	M	H	H	H	H	M	H	H	H	M	M	H	H
(EL)	M	L	L	L	N	N	L	L	L	N	N	N	N	L	N	N	N	N	L	N
(EM)	H	H	M	M	L	L	M	H	M	L	L	L	L	M	N	N	L	L	M	L
(EH)	VH	VH	H	H	VH	M	H	VH	H	M	M	H	H	H	N	N	M	H	H	H

LEGEND:

CL=Low level cracking	CM=Medium level cracking	CH =High level cracking
PL=Low level potholes	PM=Medium level pothole	PH =High level potholes
RL=Low level raveling	RM=Medium level raveling	RH=High level raveling
PAL=Low level patching	PAM=Medium level patching	PAH=High level patching
RUL=Low level rutting	RUM=Medium level rutting	RUH=High level rutting
EL=Low level edge failure	EM=Medium level edge failure	EH=High level edge failure
N= Negligible	L= Low	M=Medium
H = High	VH=Very High	

4.7 SUMMARY

In the current Chapter, pavement condition and roughness data collected through field surveys was discussed in detail. Data collected for calibration of Bump Integrator and its standardization at different operating speeds were presented. Also the procedure adopted for conducting expert opinion survey to know the weights of the various distress parameters has been presented.

CHAPTER 5

DEVELOPMENT OF CORRELATION BETWEEN ROUGHNESS AND DISTRESS PARAMETERS

5.1 BACKGROUND

In the previous chapter the data collection process was explained in detail. In this chapter the development of the following mathematical models has been discussed using this data.

- To calibrate the Bump Integrator using MERLIN
- To standardize the Bump Integrator at different operating speeds
- To predict the roughness from pavement distress parameters

5.2 CALIBRATION OF BUMP INTEGRATOR USING MERLIN

The Towed Fifth Wheel Bump Integrator is a kind of response type Unevenness Index (UI) measuring system and the UI measured by this system depends on the actual unevenness of the road surface and also on the combined effect of dynamics due to the vibration of the towing vehicle and the instrument. Hence, it is absolutely essential to calibrate this equipment before being used for field data collection. Bump Integrator was calibrated at BITS-Pilani with MERLIN before the actual surveys were being conducted.

The MERLIN D-Values obtained during the data collection on calibrated sections (Table 4.5) were converted into Bump Integrator roughness values. For this purpose, a relationship suggested by Cundill (1991) and Sayers et al., (1986) between the MERLIN D-Values and the Unevenness Index (mm/km) values obtained using Bump Integrator was used. It has been shown in Equation 5.1.

$$BI = 574 + 29.9\ D \qquad (5.1)$$

Where,

BI = Unevenness Index (mm/km) obtained using Bump Integrator

D = MERLIN D-value

Unevenness Index values obtained using from MERLIN D-Values have been presented in Table 5.1. The roughness values found on the calibrated sections using Bump Integrator at the standard speed of 32 km/hr are also being shown in the table for comparison.

Table 5.1 Roughness values obtained from MERLIN and Bump Integrator

Stretch No.	MERLIN D-Value	UI values from MERLIN using Eq. 4.1 (mm/km)	UI value Obtained from Bump Integrator (mm/km)
1	82.5	3041	3083
2	86.5	3160	3147
3	88.5	3220	3271
4	95	3414	3445
5	64.7	2508	2516
6	65.6	2535	2615

A close look at the roughness values obtained from both the instruments shows very little variation. With a view to neutralize these disparities, a simple linear regression model was developed as shown in Eq. 5.2. The relationship has also been shown graphically in Fig 5.1.

$$UI_c = 1.0118 * (UI_f) - 68.69 \qquad r^2 = 0.9925 \qquad (5.2)$$

Where,

UI_c = Corrected Unevenness Index

UI_f = Measured Unevenness Index in the field using Bump Integrator

The equation thus developed has been used for correcting the Unevenness Index values obtained in the field throughout the study.

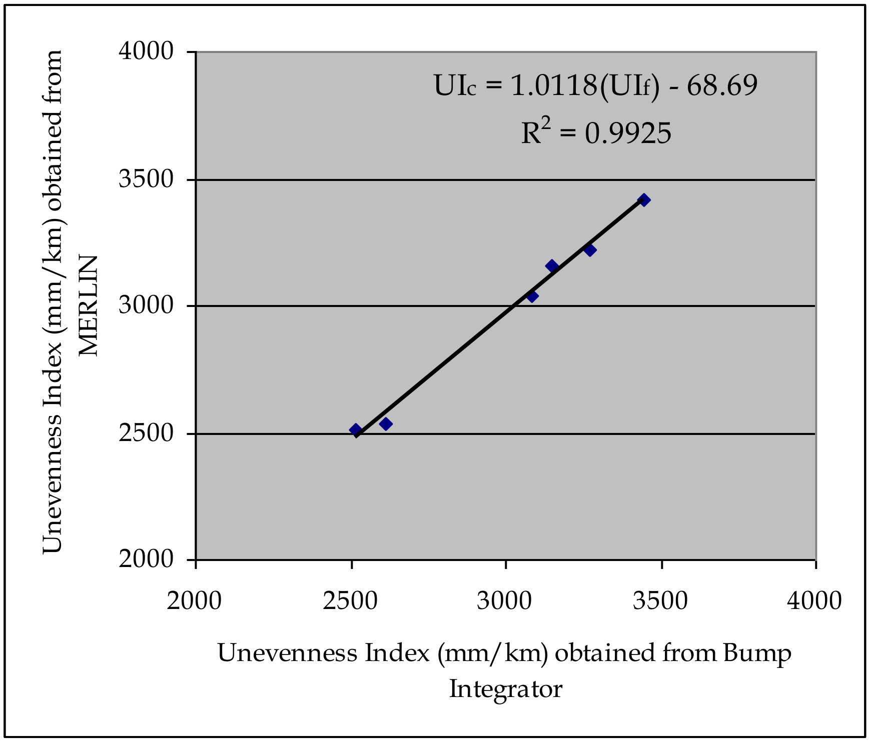


Fig 5.1: Relationship between Roughness Values obtained from Bump Integrator and MERLIN

5.3 STANDARDIZING PAVEMENT UNEVENNESS INDEX AT DIFFERENT OPERATING SPEEDS

The problem of quantifying or measuring the road roughness on a given stretch of road has always been a challenging task. Several agencies have tried to standardize the roughness measurement process for uniformity. Consequently, a number of instruments have been developed and standardized at a particular speed for the collection of pavement roughness data. Among these, Towed Fifth Wheel Bump Integrator is the most popular equipment used in several developing countries because it is not expensive and requires little maintenance. The basic model of Towed Fifth Wheel Bump Integrator was developed by Transport and Road Research Laboratory, UK and was calibrated at a standard speed of 32 km/hr. Several agencies have also developed similar kind of equipment and standardized at particular speeds. In India, CRRI has also developed Towed Fifth Wheel Bump Integrator which is also standardized at a speed of 32 km/hr and has been used in the current study.

While conducting Bump Integrator survey in the field, it was found difficult to maintain the standard speed of 32 km/hr on a few stretches on the Major District Roads and State Highways due to excessive pavement distresses and the heterogeneous traffic mix with a substantial proportion of slow-moving vehicles. On the other hand, the higher operating speeds maintained by the traffic stream on primary road system like National Highways, sometimes, made it difficult to move the Bump Integrator at the standard operating speed. In this context, it was felt necessary to develop relationships between the roughness values obtained by running the Bump Integrator at different operating speeds with those obtained at the standard operating speed of 32 km/hr. It is to be noted here that in the present study, while studying the sensitivity of speed on the Bump Integrator readings, dynamics of the vehicle was not considered. To ensure that the effect of vehicle dynamics is minimum a moderately new vehicle in good condition was used for data collection and to maintain uniformity.

The UI values obtained at different operating speeds varying from 10 to 50 km/hr with an increment of 5 km/hr and at the standard operating speed, presented in the Tables 4.8 and 4.9 on uneven and even surfaces respectively have been used for developing mathematical relationships. As discussed in section 4.4.1, the even surface has been defined when the IRI value was less than 2500 mm/km and the stretches with the higher values were considered as uneven. The relationship between Unevenness Index and the speed of the

Bump Integrator for the twenty uneven surfaces has been shown in Fig 5.2. It may be observed that the stretches were having varying unevenness indices. For the standard speed of 32 km/hr the index ranges from 2770 and 4930 mm/km.

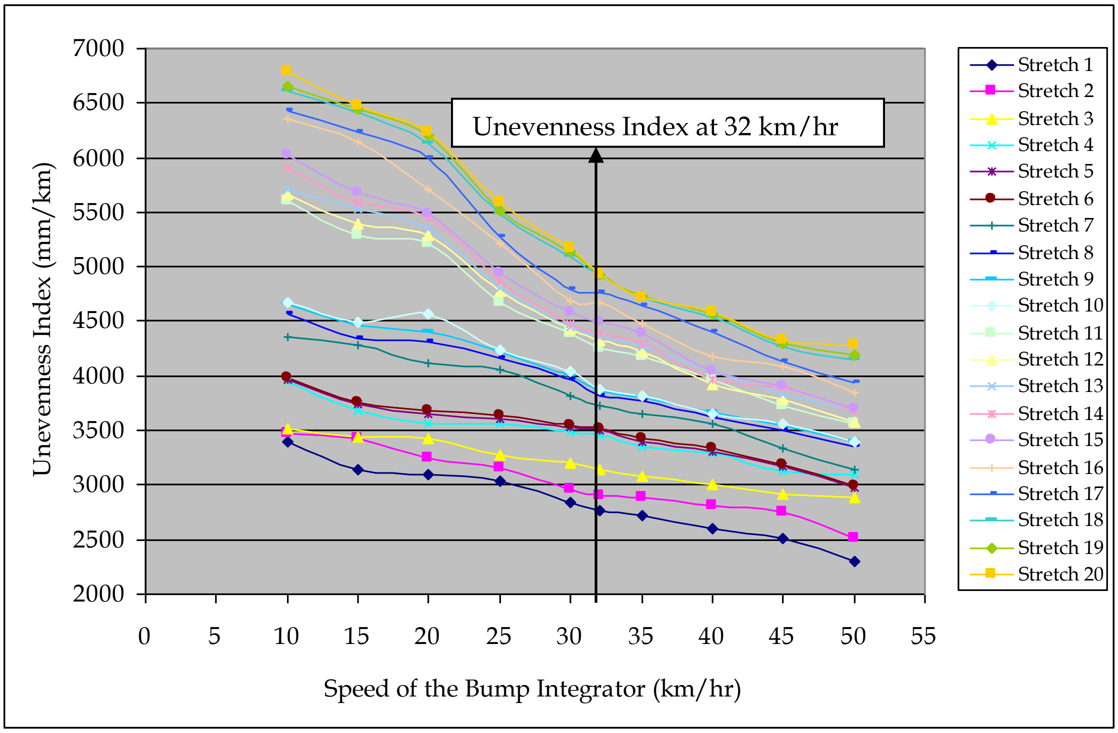


Fig 5.2: Trend of Unevenness Index values on various Uneven Stretches at different Operating Speeds

On all the stretches, the roughness values decreased with increasing running speeds. This phenomenon can be attributed to the fact that on such surfaces, when the Bump Integrator wheel travels at higher speed tends to miss out micro and small distresses on the pavement surfaces, thus showing lesser UI values. On the contrary, when it travels at lower speeds, it follows the actual profile of the road surface and the wheel covers both micro as well as macro irregularities and hence indicates higher UI values.

For even surfaces, this disparity was not observed when the Bump Integrator operated at the speeds ranging between 10 to 50 km/hr as shown in Fig. 5.3.

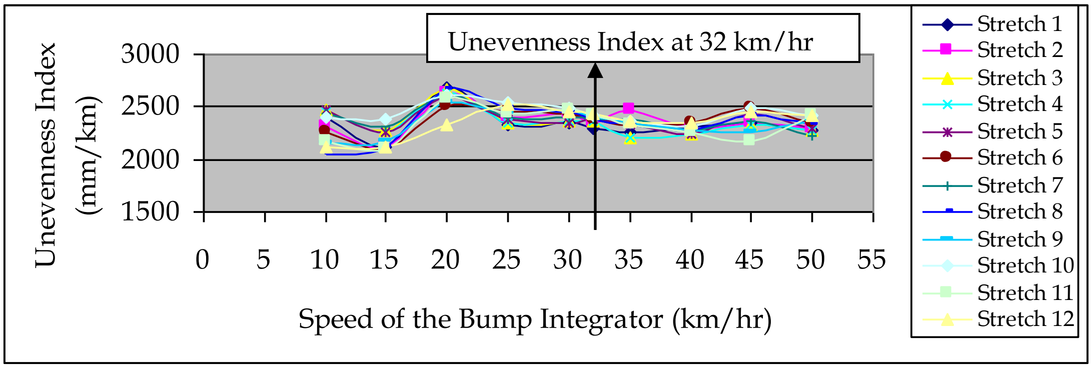


Fig 5.3: Trend of Unevenness Index Values on Various Even Stretches at Different Operating Speeds

This is quite understandable because when a vehicle travels over a smooth surface there is no distress and thus roughness is not expected to vary with speed. The variations as seen in the figure do not follow any pattern, this might be due to some local factors at the time of carrying out the survey such as presence of small stone chips, utility cuts on the wheel path or may be due to the dynamic effect caused by vehicle vibration.

In the present study, an attempt has been made to develop the representative equations for uneven surfaces for different speeds of operation to find the UI value at the standard running speed of 32 km/hr. Using SPSS software [www.spss.com] simple linear regression models have been developed between the observed UI values at standard speed as the dependent variable and the observed UI values at a particular speed of operation as the independent variable. These models are developed for the speeds between 10 and 50 km/hr with an increment of 5 km/hr. A summary of all these models with corresponding r^2 values have been presented in Table 5.2. It might be observed from the table that the constant value in the models was positive for the operating speed of 10km/hr to 30km/hr and then it was negative. It shows that the roughness is inversely proportional to operating speed of the Bump Integrator.

Table 5.2: Regression Equations to find the Unevenness Index at Standard Speed

Running Speed (km/hr)	Equation to find the Unevenness Index (mm/km) at 32km/hr ($(UI)_{32}$)	r^2
10	$0.56(UI)_{10}+1140$	0.972
15	$0.58(UI)_{15}+1187$	0.973
20	$0.62(UI)_{20}+1070$	0.976
25	$0.81(UI)_{25}+450$	0.991
30	$0.95(UI)_{30}+106$	0.997
35	$1.07(UI)_{35} - 155$	0.997
40	$1.17(UI)_{40} - 350$	0.989
45	$1.28(UI)_{45} - 555$	0.992
50	$1.25(UI)_{50} - 212$	0.987

Where

$(UI)_{10}$ - $(UI)_{50}$ are the Unevenness Index values at different operating speeds from 10 to 50.

For Example, if the UI obtained at 25km/hr speed is 3200mm/km, the actual UI at standard operating speed is 3042 mm/km (0.81*3200+450). In addition, an attempt was also made to develop a generalized equation between observed UI values at the standard operating speed of 32km/hr and the observed UI values at any given speed of operation running between 10 and 50 km/hr. A multiple non-linear regression model has been developed by considering the UI at standard speed as the dependent variable and UI at different running speeds and the operating speeds as the independent variables. The developed relationship with corresponding r^2 values is shown in Eq. 5.3.

$$(UI)_{32km/h} = \left(\frac{V}{32}\right)^{0.4} \times ((UI)_V - 1500) + 1500 \qquad R^2 = 0.934 \qquad (5.3)$$

Where,

$(UI)_{32km/h}$ = Unevenness Index at standard operating speed of 32 km/hr

V is the operating speed

$(UI)_V$ is the UI at operating speed V

5.3.1 Model Validation

To verify the accuracy of the developed models, UI values for all the operating speeds has been separately measured on five different uneven stretches. The values corresponding to the standard speed was then calculated using the equations shown in Table 5.2 and Eq. 5.3. A summary of the observed UI values and estimated UI values from individual and generalized equations along with the deviations has been presented in Table 5.3. Percentage of deviation has been calculated using the Eq. 5.4.

$$\text{Percentage of Deviation}= \frac{((\text{Observed}(UI)_{32})-(\text{Expected}(UI)_{32}))}{(\text{Observed}(UI)_{32})}\times 100 \qquad (5.4)$$

Where, $(UI)_{32}$ is the Unevenness Index value at 32 km/hr

Table 5.3: Calculation of Percentage of Deviation from the Observed and Expected Unevenness Index Values

Stretch	Observed UI at 32 km/hr	Running Speed (Km/hr)	Observed UI at Running Speed mm/km	Expected UI at 32km/hr using Individual Equation shown in Table 5.2	% of error	Expected UI at 32km/hr using Generalized Equation 5.3	% of Deviation
I	2810	10	3302	2989	-6.37	2632	6.35
	2810	15	3182	3033	-7.92	2742	2.41
	2810	20	3118	3003	-6.87	2841	-1.09
	2810	25	3062	2930	-4.28	2915	-3.74
	2810	30	2862	2825	-0.53	2827	-0.62
	2810	35	2732	2768	1.49	2777	1.18
	2810	40	2624	2720	3.20	2729	2.88
	2810	45	2526	2678	4.69	2676	4.77
	2810	50	2443	2842	-1.13	2627	6.50

Stretch	Observed UI at 32 km/hr	Running Speed (Km/hr)	Observed UI at Running Speed mm/km	Expected UI at 32km/hr using Individual Equation shown in Table 5.2	% of error	Expected UI at 32km/hr using Generalized Equation 5.3	% of Deviation
II	3782	10	4586	3708	1.95	3438	9.10
	3782	15	4342	3705	2.03	3599	4.84
	3782	20	4192	3669	2.99	3731	1.36
	3782	25	4096	3768	0.38	3852	-1.85
	3782	30	3932	3841	-1.57	3870	-2.33
	3782	35	3714	3819	-0.98	3795	-0.34
	3782	40	3612	3876	-2.49	3809	-0.72
	3782	45	3422	3825	-1.14	3703	2.09
	3782	50	3212	3803	-0.56	3547	6.22
III	4318	10	5607	4280	0.88	4079	5.53
	4318	15	5281	4250	1.58	4292	0.59
	4318	20	5220	4306	0.27	4582	-6.12
	4318	25	4671	4234	1.96	4373	-1.27
	4318	30	4380	4267	1.18	4307	0.26
	4318	35	4170	4307	0.26	4267	1.17
	4318	40	3969	4294	0.56	4200	2.74
	4318	45	3729	4218	2.31	4055	6.10
	4318	50	3562	4241	1.79	3965	8.18
IV	4920	10	6528	4796	2.53	4657	5.34
	4920	15	6252	4813	2.17	5010	-1.82
	4920	20	5800	4666	5.16	5063	-2.91
	4920	25	5418	4839	1.65	5050	-2.63
	4920	30	5096	4947	-0.55	5004	-1.71
	4920	35	4740	4917	0.07	4858	1.26
	4920	40	4573	5000	-1.63	4860	1.22
	4920	45	4370	5039	-2.41	4789	2.66
	4920	50	4229	5074	-3.14	4762	3.20
V	5010	10	6868	4986	0.48	4871	2.78
	5010	15	6506	4960	0.99	5197	-3.74
	5010	20	5997	4788	4.43	5226	-4.32
	5010	25	5552	4947	1.26	5171	-3.21
	5010	30	5278	5120	-2.20	5182	-3.43
	5010	35	4913	5102	-1.83	5038	-0.55
	5010	40	4638	5076	-1.33	4931	1.58
	5010	45	4505	5211	-4.02	4944	1.32
	5010	50	4424	5318	-6.15	4995	0.29
Mean Absolute Percentage Deviation					**2.29**		**2.98**

It may be observed from Table 5.3 that there was not much variation between the UI values with those of the predicted values using individual and generalized equations. The Mean Absolute Percentage Deviation (MAPD) of the values with the developed individual and generalized equations from those of the observed values were 2.29 and 2.98 respectively. Thus the equations were found to be satisfactory for predicting UI values when the data could not be collected at standard operating speed of 32 km/hr. Also it was observed that the individual equations were found to be more accurate than generalized.

With a view to visually observe the difference between the observed and with the estimated values, plots are being drawn with predicted UI values at 32 km/hr as ordinate and the observed UI values at standard operating speed as abscissa. The plots for different speeds are shown in Fig. 5.4 to 5.12. Ideally all the points both observed and predicted should lie on this line if there was no variation between the values. However, it was also observed that the amount of scatter was not high in any of the cases. Only in few cases, the variation between observed and predicted values was more than 5%. These might be due to minor errors in data collection.

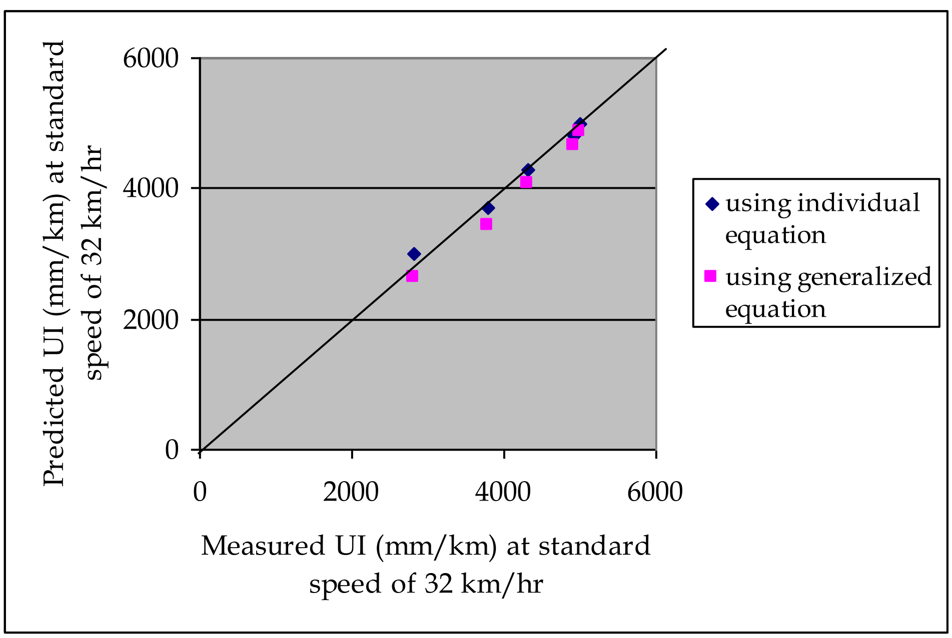


Fig 5.4: Plot between Predicted UI Values at 32 km/hr Speed from those Obtained at 10 km/hr Running Speed and Observed UI Values at 32 km/hr Speed

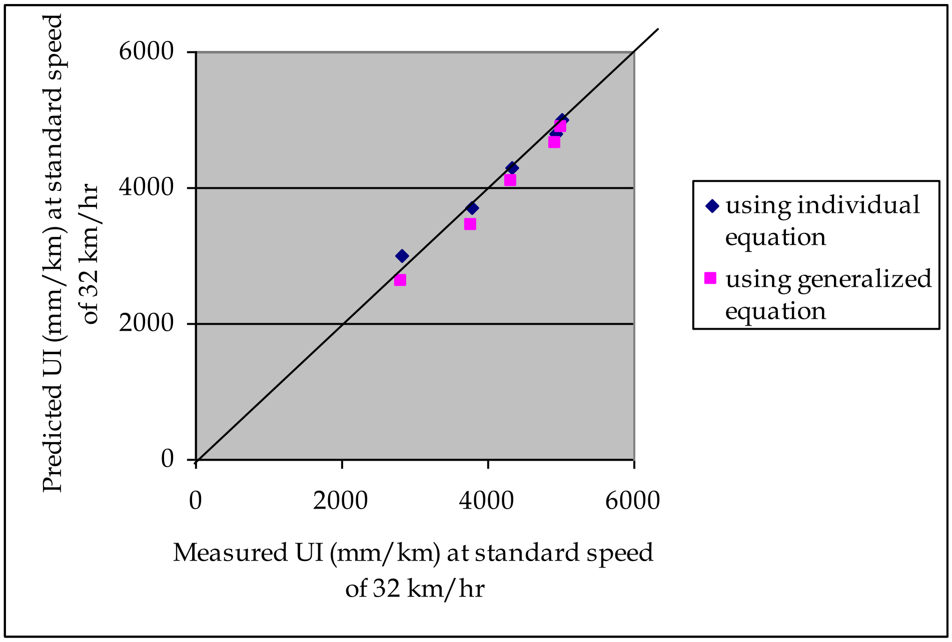


Fig 5.5: Plot between Predicted UI Values at 32 km/hr Speed from those Obtained at 15 km/hr Running Speed and Observed UI Values at 32 km/hr Speed

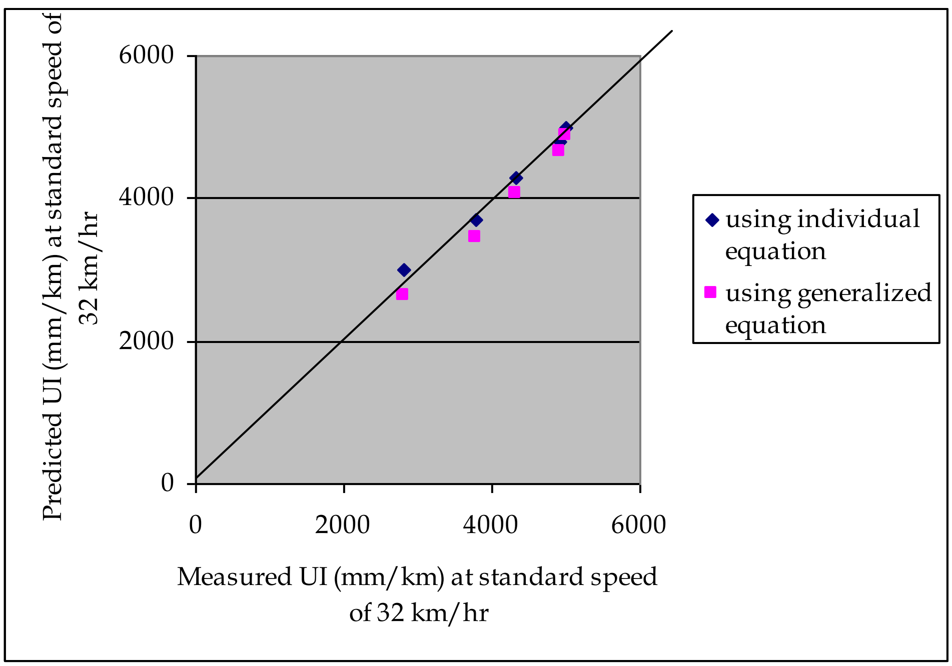


Fig 5.6: Plot between Predicted UI Values at 32 km/hr Speed from those Obtained at 20 km/hr Running Speed and Observed UI Values at 32 km/hr Speed

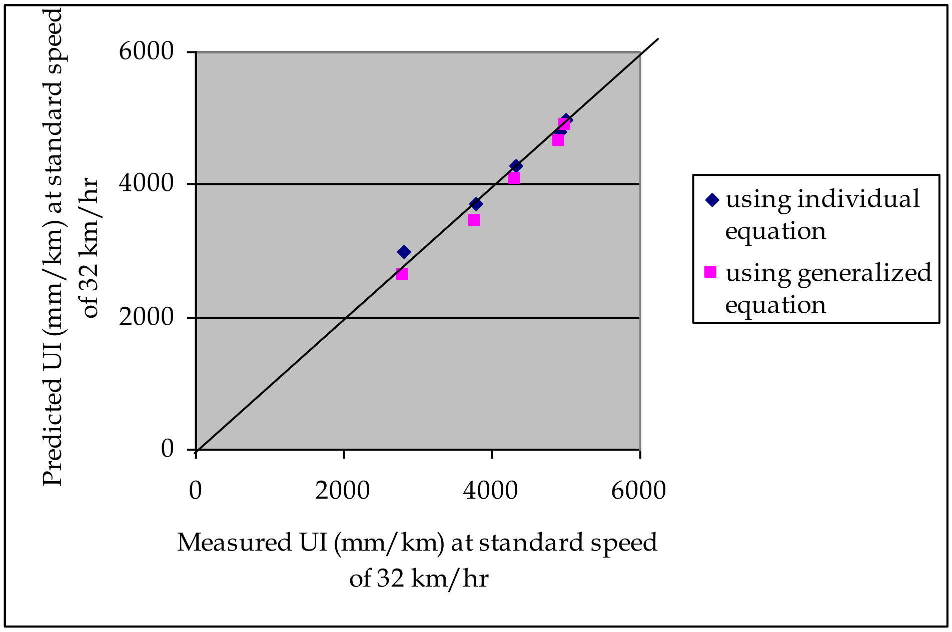


Fig 5.7: Plot between Predicted UI Values at 32 km/hr Speed from those Obtained at 25 km/hr Running Speed and Observed UI Values at 32 km/hr Speed

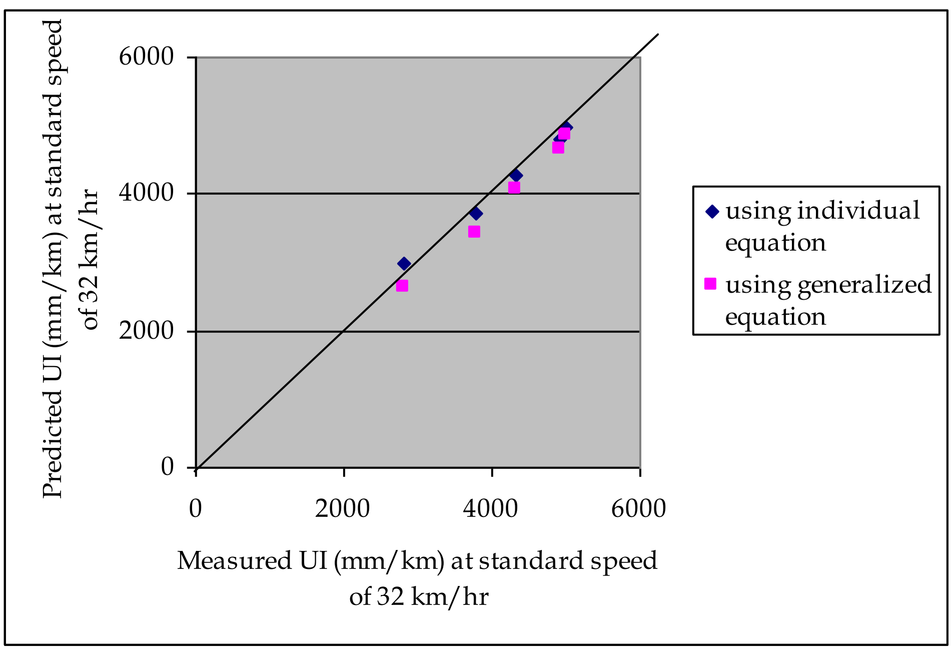


Fig 5.8: Plot between Predicted UI Values at 32 km/hr Speed from those Obtained at 30 km/hr Running Speed and Observed UI Values at 32 km/hr Speed

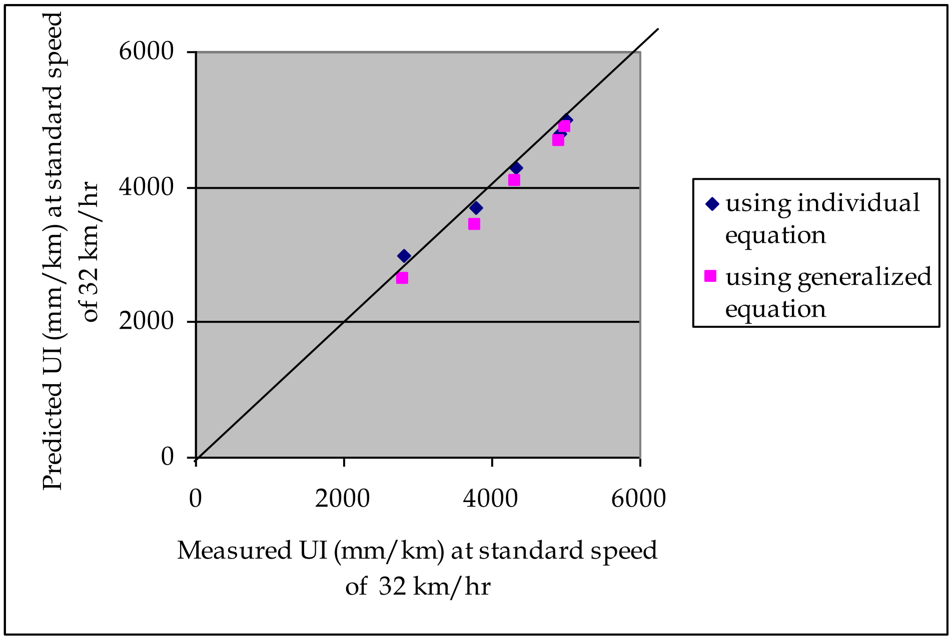


Fig 5.9: Plot between Predicted UI Values at 32 km/hr Speed from those Obtained at 35 km/hr Running Speed and Observed UI Values at 32 km/hr Speed

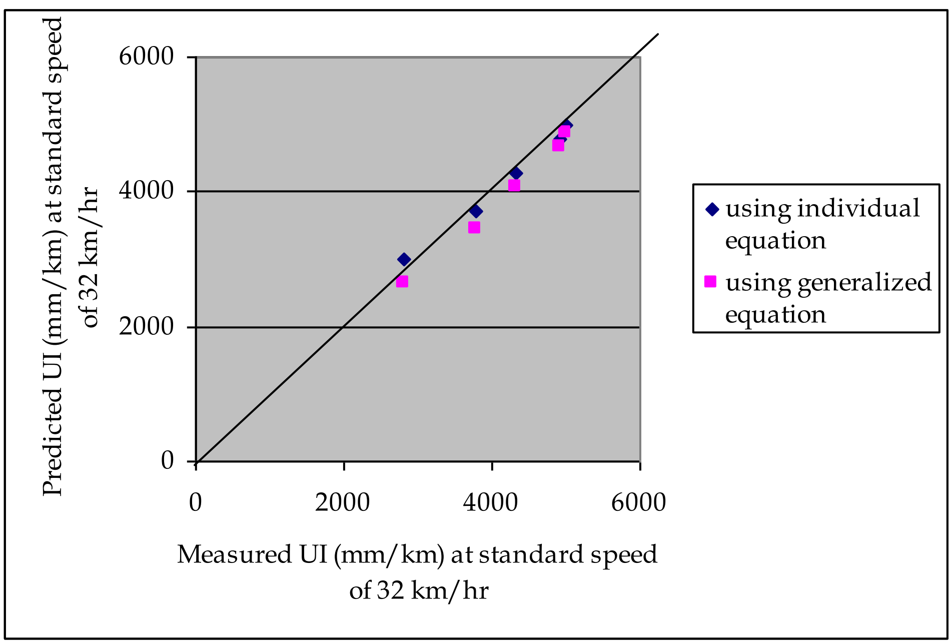


Fig 5.10: Plot between Predicted UI Values at 32 km/hr Speed from those Obtained at 40 km/hr Running Speed and Observed UI Values at 32 km/hr Speed

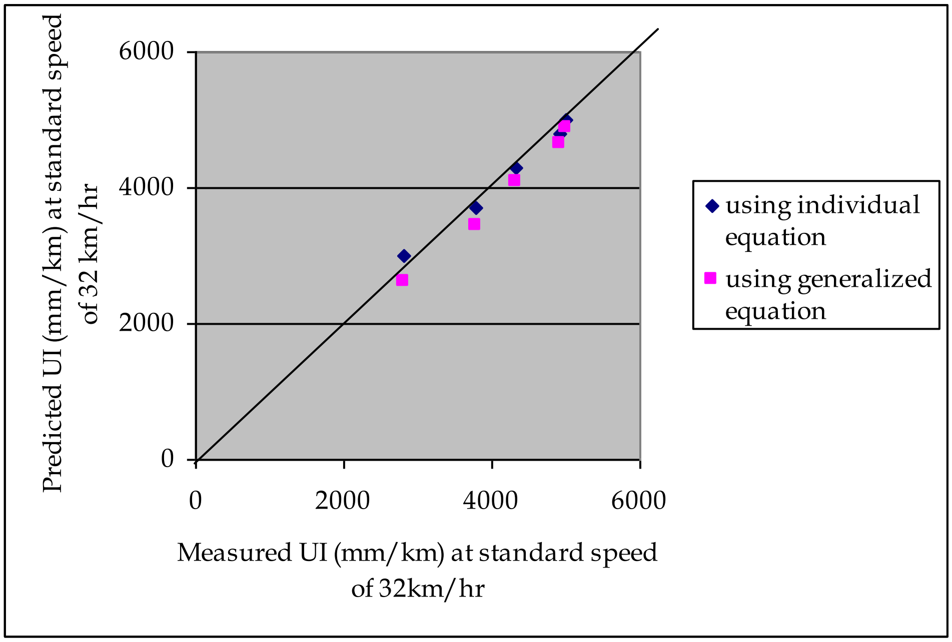


Fig 5.11: Plot between Predicted UI Values at 32 km/hr Speed from those Obtained at 45 km/hr Running Speed and Observed UI Values at 32 km/hr Speed

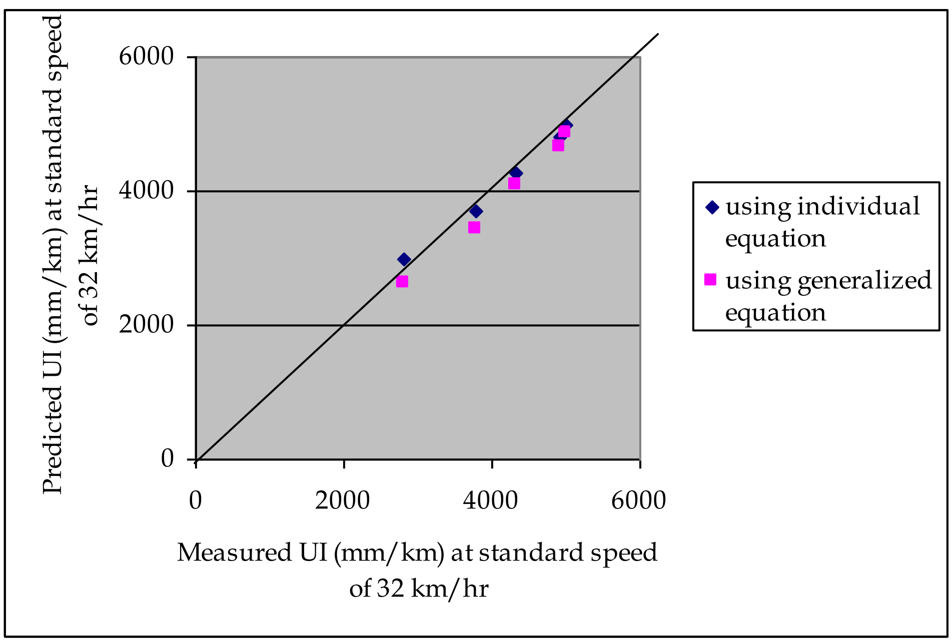


Fig 5.12: Plot between Predicted UI Values at 32 km/hr Speed from those Obtained at 50 km/hr Running Speed and Observed UI Values at 32 km/hr Speed

5.4 PAVEMENT ROUGHNESS MODEL DEVELOPMENT

Pavement roughness is an overall indicator of the quality of a pavement and it adversely affects not only the vehicle riding quality but also the road user cost. It is usually manifested as a combined effect of different individual pavement deterioration parameters such as cracking, potholes, raveling, patching and rutting.

Though it looks like a simple exercise to express the road roughness as a factor of these individual parameters, it is difficult to find the contribution of each parameter separately in the overall roughness of a stretch of pavement. It might be observed from the review of literature that most of the attempts have been made in the direction of roughness prediction rather than expressing the roughness as a function of individual deterioration parameters. Since roughness represents the overall condition of a pavement at any given point of time, in the present study, an attempt has been made to develop a model representing it, as a function of a few selected deterioration parameters.

5.4.1 Standardization of Roughness Values Obtained at Different Operating Speeds

Bump Integrator model –V used in the present study has the facility to record the running speed. It was observed that in some of the stretches, standard operating speed of 32 km/hr cannot be maintained due to the practical difficulties as discussed earlier. Hence, the UI values obtained at other than standard operating speeds are converted into the standard speed using the equation 5.3, and these values are being used in the model development.

5.4.2 Minimum UI Value on a Freshly Laid Road Surface

On a few freshly overlaid pavements including different functional class of highways such as National Highways (NHs), State Highways (SHs) and

Major District Roads (MDRs) roughness were measured using Bump Integrator running at standard speed of 32 km/hr. This study resulted with an average initial UI value of 1750 mm/km (IRI=2.4 m/km) on NHs, 2025 mm/km (IRI=2.8 m/km) on SHs and 2225 mm/km (IRI=3.0 m/km) on MDRs. The values clearly show that the quality of pavement surfaces deteriorate from NHs to SHs to MDRs. These values, being free from the surface distresses, have been deducted from the observed roughness and the excess values are considered as due to the distress parameters present on the pavement surface.

5.4.3 Converting the UI into International Roughness Index (IRI)

Generally, roughness is expressed in terms of International Roughness Index (IRI) and it is expressed as m/km. In this study also the UI values obtained from the Bump Integrator has been converted into IRI values and then used for the model development. In the International Road Roughness Experiment (IRRE) conducted in Brazil (Sayers et al., 1986), a standard Bump Integrator was calibrated against the IRI standard and a relationship was established as shown in Eq. 5.5 and number of researchers have used this equation in different situations (Odoki and Kerali, 2000).

$$IRI = 0.0032\,(BI)^{0.89} \qquad (5.5)$$

Where,

IRI = International Roughness Index (m/km)

BI =Unevenness Index obtained from Bump Integrator (mm/km)

The same equation has been used in this study for converting bump integrator readings to IRI values.

5.4.4 Normalization of the Distress Parameters

The extent data (collected in terms of area) of all the pavement distress parameters namely cracking, potholes, patching and raveling collected in three severity levels were normalized by converting them into percentage of the total area considered using the Eq. 5.6.

$$PAD = (AD * 100 / A) \tag{5.6}$$

Where,

PAD = Percentage Area of Distress parameters

AD= Area of Distress parameter

A = Total area of the pavement considered

Only rutting is expressed in terms of meter per km as it follows a linear path.

5.4.5 Model Development

The pavement distress data and roughness data collected along the marked wheel path over 858 uniform stretches of 50 m length covering different NHs, SHs and MDRs have been used for modeling. Data on the randomly selected 770 stretches (90% of the observed values) was used for model development and the data on remaining 88 stretches (approximately 10% of the observed values) are kept aside for the model validation. Pavement distress data used for model development is presented in *Appendix -4.*

A multiple linear regression model has been developed to express the relationship between IRI and pavement distress parameters using SPSS software [www.spss.com]. In this model IRI value was taken as the dependent variable and the measured pavement distresses namely, cracking, potholes, patching, raveling and rutting in three severity levels namely low, medium and high, were considered as independent variables. Although the distresses independently contribute to the roughness, there may be auto correlation among the distress parameters. Thus the correlation coefficients among all the independent variables were found independently to identify the variable having high correlation. The correlation coefficients between the independent variables are presented in the Table 5.4.

Table 5.4: Correlation Coefficients between the Independent Variables

	IRI	RL	RM	RH	PAL	PAM	PAH	PL	PM	PH	CL	CM	CH	RUL	RUM	RUH
IRI	1.00															
RL	0.65	1.00														
RM	0.62	-0.28	1.00													
RH	0.54	-0.23	-0.01	1.00												
PAL	0.76	-0.13	-0.13	-0.16	1.00											
PAM	0.60	-0.28	-0.12	0.14	-0.06	1.00										
PAH	0.56	-0.29	-0.18	0.07	-0.11	-0.06	1.00									
PL	0.48	-0.31	0.06	0.04	-0.08	0.16	-0.01	1.00								
PM	0.86	0.01	0.09	-0.04	0.10	-0.02	-0.10	0.04	1.00							
PH	0.51	-0.11	0.09	0.19	0.00	0.04	-0.07	0.30	0.20	1.00						
CL	0.16	-0.12	-0.04	-0.14	-0.15	-0.12	-0.06	-0.12	-0.12	-0.13	1.00					
CM	0.61	-0.12	-0.16	-0.09	-0.15	-0.16	0.07	-0.11	-0.05	-0.14	0.11	1.00				
CH	0.73	-0.19	-0.16	-0.14	-0.16	-0.12	0.17	-0.12	-0.12	-0.18	0.16	0.11	1.00			
RUL	0.42	-0.09	-0.35	-0.02	0.03	0.03	0.03	-0.14	-0.21	-0.21	0.16	0.17	0.28	1.00		
RUM	0.57	0.07	-0.04	-0.06	-0.07	-0.01	-0.05	-0.01	-0.01	-0.02	0.06	0.02	0.08	-0.18	1.00	
RUH	0.52	-0.05	0.02	0.08	-0.01	-0.02	0.25	-0.11	-0.28	-0.20	0.04	0.04	0.17	-0.39	-0.36	1.00

It may be observed that, the correlation coefficients among all the independent variables were quite low and hence all the variables were considered for developing the model.

The developed model between IRI and distresses with corresponding R^2 value is presented through Equation 5.7. It is to be noted here that IRI values used in the model development are the values obtained after deducting the initial IRI values (discussed in section 5.4.2) i.e. IRI values due to distresses only.

$$\begin{aligned}\textbf{IRI}_{\textbf{D}}\ \textbf{(m/km)} = {} & 0.0148*RL+ 0.0219*RM+ 0.0343*RH+ 0.0307*PAL+ \\ & 0.0425*PAM+ 0.0437*PAH+ 0.1089*PL+ 0.1392*PM+ \\ & 0.1631*PH+0.0113*CL +0.0179*CM+ 0.0310*CH+ \\ & 0.0017*RUL+ 0.0024*RUM+ 0.0034*RUH \quad (R^2 = 0.954) \qquad (5.7)\end{aligned}$$

Where, IRI_D = IRI due to distresses only in cm/km

RL = Low Severity Raveling in %of area

RM = Medium Severity Raveling in %of area

RH = High Severity Raveling in %of area

PAL = Low Severity Patching in %of area

PAM = Medium Severity Patching %of area

PAH = High Severity Patching %of area

PL= Low Severity Potholes in %of area

PM = Medium Severity Potholes in %of area

PH = High Severity Potholes in %of 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

RUM = Medium Severity Rutting in meters

RUH = High Severity Rutting in meters

To develop the relationship between IRI and the distress parameters, Eq. 5.7 has been modified by adding a constant of the initial roughness observed on the newly overlaid pavement surfaces. Accordingly, the total roughness obtained from the model is presented in equation 5.8. It might be noted here that the constant value 'A' would be different for various categories of roads as already discussed in article 5.4.2.

$$\textbf{IRI (m/km)} = A + 0.0148*RL + 0.0219*RM + 0.0343*RH + 0.0307*PAL + 0.0425*PAM + 0.0437*PAH + 0.1089*PL + 0.1392*PM + 0.1631*PH + 0.0113*CL + 0.0179*CM + 0.0310*CH + 0.0017*RUL + 0.0024*RUM + 0.0034*RUH \quad (5.8)$$

Where

A = 2.4 for National Highways

= 2.8 for State Highways

= 3.0 for Major District Roads

To check the statistical validity of the model, the well known 'student-t' values and the confidence intervals for each coefficient have been calculated and are presented in Table 5.5. The acceptable 'student-t' value for 95% confidence level is 1.645 (Miller and Miller, 2005). It has been observed from the table that the 'student-t' values for all the distress parameters were greater than 1.645, hence are statistically acceptable.

Table 5.5: Statistics for the Roughness Model

S.No	Distress Parameters	Coefficients	Student-t	95% Confidence Interval for Coefficients	
				Lower Bound	Upper Bound
1	RL	0.0148	27.87	0.0138	0.0158
2	RM	0.0219	23.74	0.0201	0.0237
3	RH	0.0343	34.71	0.0323	0.0362
4	PAL	0.0307	26.55	0.0285	0.0330
5	PAM	0.0425	29.57	0.0397	0.0453

S.No	Distress Parameters	Coefficients	Student-t	95% Confidence Interval for Coefficients	
				Lower Bound	Upper Bound
6	PAH	0.0437	24.15	0.0402	0.0473
7	PL	0.1089	13.80	0.0934	0.1244
8	PM	0.1392	6.50	0.0971	0.1812
9	PH	0.1631	11.59	0.1355	0.1907
10	CL	0.0113	3.87	0.0056	0.0170
11	CM	0.0179	8.68	0.0138	0.0219
12	CH	0.0310	18.51	0.0277	0.0343
13	RUL	0.0017	8.80	0.0013	0.0021
14	RUM	0.0024	8.70	0.0018	0.0029
15	RUH	0.0034	8.20	0.0026	0.0038

The following observations were made from the roughness model presented in the Eq. 5.7.

- The coefficients for potholes were quite high as compared to other distress parameters. It is a established fact that the contribution of potholes is higher as compared to other distresses on the roughness of a pavement stretch. It might also be observed that the coefficient for small, medium and high severity potholes shows increasing trend with the values of 0.1089, 0.1392 and 0.1631 respectively, which is quite logical.

- Coefficients for patching are also significant with the values of 0.0307, 0.0425 and 0.0437 for small, medium and high respectively. It was observed that, in most of the cases patching was not being done according to the standard methods and there was a level between existing pavement and patching surface. In addition, it was also observed that the surface of the patching was not properly leveled.

- Low severity cracking had negligible effect on roughness whereas high severity cracking had significant effect with coefficients of 0.0113, 0.0179 and 0.0310 respectively. The impact of high severity cracking is almost equal to low severity patching.

- Coefficients for rutting were not very significant. Rutiing was prominently visible mostly on National Highways due to channelized movement of traffic with clear wheel paths. It was observed that, in most of the stretches where the distress was found had almost uniform rutting over a short length. Hence, when the Bump Integrator wheel passes over the uniformly rutted pavement surface, there was little undulation and thus its influence on roughness was not significant.

5.4.6 Model Validation

It has been already discussed that 10% of the randomly selected data points were kept aside for validation purpose. Using this data, the IRI values were predicted by simple substitute of the pavement distress parameters in the model developed in this study. Then the calculated and observed data were statistically compared and Mean Absolute Percentage Deviation (MAPD) was calculated using Eq. 5.9 to determine the robustness of the model as shown in Table 5.6

$$\text{Absolute Percentage of Deviation} = \left| \frac{\text{Observed(IRI)} - \text{Predicted(IRI)}}{\text{Observed(IRI)}} \times 100 \right| \quad (5.9)$$

It may be observed that there was no significant variation between the observed and the predicted IRI. However, in few stretches the deviation was in little higher side. It may be due to the fact that, all the possible distress parameters were not considered while developing the model and some of the distresses such as stripping and bleeding were possibly present in a few stretches. The MAPD between observed and predicted IRI value was 8.08, which is quite acceptable considering the data collected form different stretches of roads.

Table 5.6: Predicting the IRI Values from Pavement Distress Parameters and Calculation of Absolute Percentage Deviation

RL	RM	RH	PAL	PAM	PAH	PL	PM	PH	CL	CM	CH	RUL	RUM	RUH	IRI (m/km)	IRI-Initial IRI (m/km)	Predicted IRI m/km	Absolute % of error
14	12	7.4	51.2	9	0	6.4	0	0	0	0	0	220	0	0	6.2	3.2	3.7	16.48
12	41	32	10	5	0	0	0	0	0	0	0	200	160	0	6.2	3.2	3.4	5.15
28	19.4	0	48.6	0	0	2.64	1.36	0	0	0	0	0	160	0	6.1	3.1	3.2	1.74
0	0	26	42	19.2	12.2	0.48	0	0.12	0	0	0	0	80	0	7.2	4.2	3.8	10.17
0	0	53	0	30.4	8.6	3.2	0	4.8	0	0	0	0	0	0	7.4	4.4	4.6	4.39
0	12.2	64	0	8.4	12.8	1.4	0	1.2	0	0	0	540	0	0	7.7	4.7	4.6	1.39
25	15	13.2	9.2	10.8	18	2.8	4.2	1.8	0	0	0	400	240	100	8.4	5.4	5.5	0.21
0	13.6	20.6	0	26.8	35.2	0.84	1.36	1.6	0	0	0	340	0	0	7.8	4.8	4.8	0.15
8.28	0	16.4	16.4	12.6	24.8	0.6	0	1.12	0	10.6	9.2	200	160	60	7.4	4.4	4.5	1.50
0	0	27.2	10.12	24.64	4.8	5.2	1.64	1.2	0	25.2	0	440	0	0	7.3	4.3	4.7	8.21
0	12.68	23.2	0	12.8	17.2	1.52	0	1.8	0	30.8	0	368	100	0	7.4	4.4	4.2	3.37
0	0	45	45	4.56	0	0.7	1.3	0	0	3.44	0	280	0	0	7.0	4.0	3.9	1.94
87	13	0	0	0	0	0	0	0	0	0	0	300	0	0	4.7	2.3	2.1	9.93
88.4	11.6	0	0	0	0	0	0	0	0	0	0	400	0	0	5.1	2.7	2.2	17.86
88.2	11.8	0	0	0	0	0	0	0	0	0	0	0	0	0	4.0	1.6	1.6	3.60
100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.2	1.8	1.5	15.86
100	0	0	0	0	0	0	0	0	0	0	0	0	20	0	4.1	1.7	1.5	8.18
66.8	4.8	0	28.4	0	0	0	0	0	0	0	0	240	80	0	5.4	3.0	2.6	13.28
76.4	0	9.2	14.4	0	0	0	0	0	0	0	0	320	0	0	5.2	2.8	2.4	14.18
20.4	8	4	52.8	13.1	0	1.7	0	0	0	0	0	320	0	0	5.8	3.0	3.5	17.73
43.6	10.4	0	33.88	9.2	1.52	0	1.4	0	0	0	0	320	120	0	6.0	3.2	3.4	5.99
49.12	10.8	4	30.08	4.8	0	0	1.2	0	0	0	0	400	0	0	5.5	2.7	3.1	12.90
35.8	0	20.6	24.2	19.4	0	0	0	0	0	0	0	280	0	0	5.5	2.7	3.3	20.41
27.4	4.8	20.6	13.48	31.2	2.52	0	0	0	0	0	0	260	160	0	6.4	3.6	3.9	9.32
84.6	0	0	0	0	0	0	0	0	12.2	1.28	1.92	320	0	0	4.9	2.1	2.0	3.06

RL	RM	RH	PAL	PAM	PAH	PL	PM	PH	CL	CM	CH	RUL	RUM	RUH	IRI (m/km)	IRI-Initial IRI (m/km)	Predicted IRI m/km	Absolute % of error
73.6	20.4	0	0	0	0	0	0	0	0	5.52	0.48	600	0	0	5.6	2.8	2.7	4.85
64.4	20.8	0	0	0	0	0	0	0	6.4	3.6	4.8	420	140	0	5.3	2.5	2.7	8.14
82.4	0	0	0	0	0	0	0	0	12.8	2.4	2.4	120	0	0	4.5	1.7	1.7	0.09
47.2	13.6	6.8	0	0	0	0	0	0	18.4	7.6	6.4	160	0	0	4.9	2.1	2.0	3.66
52	16	1.6	8	10.4	0	0	0	0	5.28	4.32	2.4	140	0	0	4.8	2.0	2.3	15.20
33.6	14.8	0	12.2	2.4	2.4	1.2	0	0	4.8	13	15.6	200	160	80	5.7	2.9	3.3	14.26
53.6	16.4	0	6.8	8.6	8.2	2.4	0	0	0	4	0	380	0	0	5.6	2.8	3.1	7.61
86	8	6	0	0	0	0	0	0	0	0	0	400	80	0	5.6	2.6	2.5	2.29
0	0	0	47.2	34.4	13.2	1.5	1.5	2.2	0	0	0	220	0	0	7.6	4.6	4.6	0.30
0	0	0	62	15.6	10.8	1.4	1.2	1.6	7.4	0	0	80	0	0	6.3	3.3	3.8	17.05
0	0	0	2.4	5	0	0	0	0	64	28.6	0	180	240	80	5.3	2.3	2.7	15.98
61.6	12.6	6.2	0	4.2	4.2	2	0	0	0	9.2	0	320	0	0	5.8	2.8	2.7	2.89
29.2	10.8	25.2	0	0	24.4	2.4	0	1.2	0	0	6.8	200	0	0	6.2	3.2	3.6	13.50
30.4	0	8.8	0	0	6.6	1.6	0.8	1.4	0	17.2	33.2	120	0	0	5.9	2.9	3.1	5.54
15	0	5.2	8.8	9.2	10.4	2.4	0.6	1.6	13.6	4.2	29	200	0	0	6.2	3.2	3.6	13.30
45	12.6	5.2	0	0	10.2	1.2	0.6	0.8	6.4	12.2	5.8	320	200	0	6.0	3.0	3.4	12.18
43.6	9	13.8	4.8	6.2	12.8	0.6	0.8	0.4	2.4	5.6	0	240	0	0	6.4	3.4	3.1	9.37
9.6	0	21.2	14.8	29.6	12.4	8	2.4	2	0	0	0	120	240	0	8.3	5.3	5.4	3.09
14	44.2	0	27	6.4	0	0	0	0	3.8	0	4.6	140	0	0	5.9	2.9	2.7	5.33
27.2	23.6	0	0	12.8	2.4	0	0	0	25.6	3.4	5	160	0	0	5.2	2.2	2.3	8.02
19.6	21.8	0	0	12.8	9	0	0	0	7	1.4	28.4	140	0	0	5.9	2.9	2.9	1.21
46.4	22.4	0	0	7.8	9.2	0	0	0	2.8	3.2	8.2	160	200	0	6.2	3.2	3.0	4.81
24	9.2	12.6	0	7	13.6	0	0	0	12.6	3.8	17.2	120	0	0	5.8	2.8	2.8	2.49
29.6	24.2	0	0	7.2	2.4	4.6	1.8	0	9.4	6.8	14	160	0	0	5.7	2.7	3.1	14.45
13.4	6.8	12.32	0	0	0.48	9	2.4	1.8	22	11.4	20.4	120	200	0	6.6	3.6	4.2	17.32
12.6	15	6	0	0	0	1.8	0	0	16.4	27.8	20.4	140	0	0	5.3	2.3	2.5	7.63
33.2	24.8	33.6	0	0	0	1.6	2.4	0	4.4	0	0	0	240	0	6.1	3.1	3.3	6.57
0	68	15.2	0	0	0	2.8	1.6	1.8	0	10.6	0	0	120	0	5.9	2.9	3.3	13.21
24.8	20.8	18.8	0	0	0	1.8	1.2	1.4	11.2	9	11	120	0	0	6.0	3.0	2.9	3.45

RL	RM	RH	PAL	PAM	PAH	PL	PM	PH	CL	CM	CH	RUL	RUM	RUH	IRI (m/km)	IRI-Initial IRI (m/km)	Predicted IRI m/km	Absolute % of error
28.4	17.2	9.2	0	7	4.2	2.2	0	0	12.8	10.6	8.4	160	100	0	6.3	3.3	2.9	10.52
0	12.8	37.2	12.6	0	0	0.8	0	0.6	8	24	4	180	0	0	6.0	3.0	3.1	2.78
0	25	53.2	8	8.6	0	2.8	1.2	1.2	0	0	0	360	300	60	7.2	4.2	5.2	24.53
29.4	37	27.6	0	0	0	4.4	1.6	0	0	0	0	100	0	0	6.0	3.0	3.1	3.00
0	46.8	40.4	0	0	0	9.2	2.2	1.4	0	0	0	140	0	0	7.0	4.0	4.2	4.86
0	22.6	42.4	0	0	0	4.6	4.2	2.4	0	7	16.8	0	0	0	6.9	3.9	4.1	5.37
0	7	4.8	0	5.2	0	1.4	2.2	1.8	24	31	22.6	0	160	0	5.7	2.7	3.2	17.08
5.4	60.4	27.2	0	0	0	4.4	1.8	0.8	0	0	0	0	0	0	6.8	4.0	3.2	19.93
27	29.2	31.6	8.8	0	0	1.6	0	1.8	0	0	0	160	0	0	6.1	3.3	3.1	4.08
0	0	0	0	0	0	4.8	1.4	1.2	0	52	40.6	240	60	0	6.2	3.4	3.7	6.87
5	37.2	24.8	0	0	0	2.4	0.8	3.8	0	6	20	260	100	0	6.5	3.7	4.1	13.37
92	8	0	0	0	0	0	0	0	0	0	0	0	180	0	4.9	2.1	2.0	4.89
86	12	2	0	0	0	0	0	0	0	0	0	180	0	0	4.7	1.9	1.9	3.14
9	14.6	25.2	0	13.6	8.6	4.2	1.6	1.4	7.8	4.6	9.4	160	240	140	7.0	4.2	5.0	18.26
0	41.4	20.2	24	8.6	1.4	1.2	2.6	0.6	0	0	0	140	0	0	6.5	3.7	3.6	2.79
0	5	53.6	9	11.2	0	2.4	1.6	1.2	12	4	0	80	260	0	7.4	4.6	4.3	5.41
13.6	9.2	15	27.2	0	0	6.4	16	1.4	6.4	4.8	0	100	300	0	8.5	5.7	6.0	5.04
56.6	41.4	0.0	0.0	0.0	0.0	0.0	0.3	1.7	0.0	0.0	0.0	0.0	0.0	0.0	4.7	1.9	2.1	7.23
69.6	14.0	0.0	0.0	0.0	0.0	0.6	0.9	6.9	0.0	8.0	0.0	0.0	60.0	0.0	5.4	2.6	2.9	14.02
73.8	8.0	0.0	0.0	0.0	0.0	0.4	0.6	1.2	0.0	16.0	0.0	0.0	0.0	0.0	4.9	2.1	1.9	11.74
0.0	77.6	0.0	0.0	0.0	0.0	0.8	0.1	0.1	8.0	13.4	0.0	140.0	0.0	0.0	5.2	2.4	2.4	0.79
0.0	32.3	8.0	0.0	0.0	0.0	0.9	0.1	0.7	16.0	16.0	26.0	0.0	60.0	0.0	5.4	2.6	2.6	0.04
89.2	9.2	0.0	0.0	0.0	0.0	0.1	1.5	0.0	0.0	0.0	0.0	0.0	80.0	0.0	5.0	2.2	1.9	10.28
																	Mean Absolute Percentage Error	**8.08**

LEGEND: CL=Low level cracking in %of area CM=Medium level cracking in %of area CH =High level cracking in %of area PL=Low level potholes in %of area PM=Medium level pothole in %of area PH =High level potholes in %of area RL=Low level raveling in %of area RM=Medium level raveling in %of area RH=High level raveling in %of area PAL=Low level patching in %of area PAM=Medium level patching in %of area PAH=High level patching in %of area RUL=Low level rutting in meters RUM=Medium level rutting in meters RUH=High level rutting in meters

With a view to validate, plots are also being drawn between estimated roughness values as ordinates and the observed roughness values as abscissa as shown in Fig 5.13. A 45^0 line has been drawn to see the distribution of plotted points on either side of the ideal line. From the figure, it can be observed that the majority of the points are either close to or falling on 45^0 line.

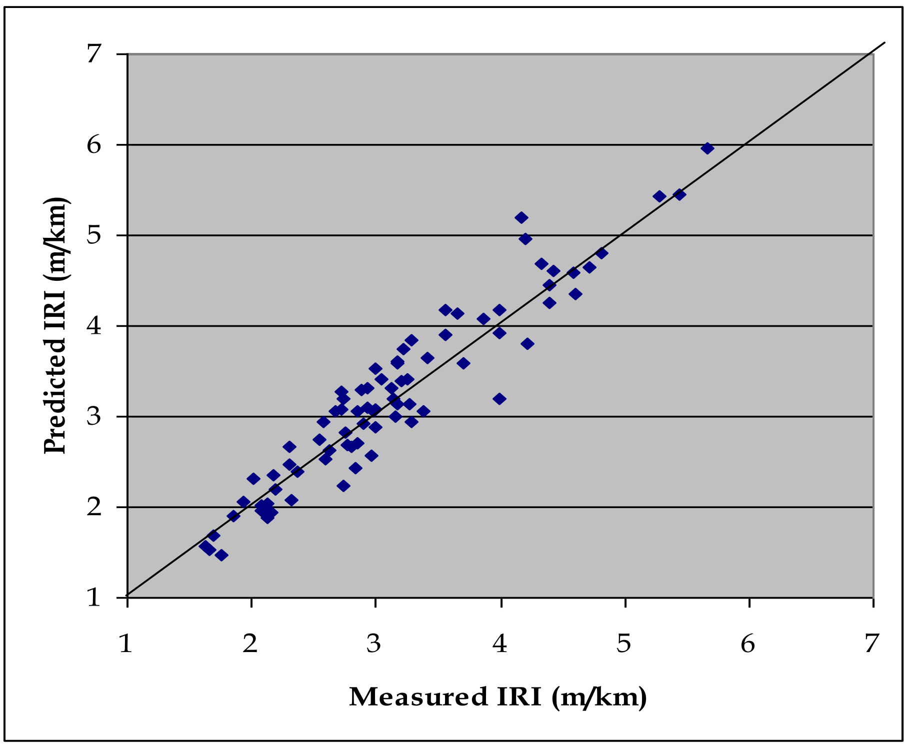


Fig 5.13: Plot between Measured Unevenness Index and Predicted Unevenness Index values

5.5 PREDICTION OF ROUGHNESS FROM INDIVIDUAL PAVEMENT DISTRESS PARAMETERS

In addition to the analysis involving combined influence of different pavement distress parameters, investigations were also carried out to check the roughness prediction capability using the model developed (Eq. 5.8) from individual distress parameters separately. This was possible as additional data was collected on a few road stretches where a single distress parameter was dominating and others were either insignificant or not present at all. It was possible to identify stretches only with rutting or raveling and accordingly the contribution of these two parameters was individually determined.

5.5.1 Prediction of IRI from Rutting

To study the influence of rutting on pavement roughness, one km road stretch on Sikar-Jaipur National Highway , having only rutting type of distress based on visual inspection was chosen for investigation. This stretch was divided into 20 uniform sections of length 50 m each and rutting measurements were made using 3m straight edge. Then Bump Integrator studies were conducted at the standard running speed of 32 km/hr. Data collected on this stretch has been presented in Table 5.7. It can be observed from the table that, the low severity values of length range between 170 m and 320 m and measured IRI values range between 2.07 and 3.06. The data for this analysis was collected on NH-11, hence as discussed earlier the initial IRI of 2.4 was deducted from the measured IRI (Table 5.7). The rutting values were substituted in the Eq. 5.7 and the IRI values were calculated. A graph was plotted between the measured and predicted IRI values and is presented in Fig. 5.14.

A close look at the Fig 5.14 and the Table 5.7 indicates that, in most of the points the difference was nominal and in some other points the variations were slightly high. This might be due to the fact that though the stretches were selected where the rutting was predominant, the possibility of having other distresses could not be ruled out. This might have caused the variation in predicted and observed values.

Table 5.7: Measured and Predicted IRI on rutted pavement surface

Name and Type of the Road	Section No.	Chainage (km)	RUL (m)	Measured IRI (m/km)	(IRI-Initial IRI) (m/km)	Predicted IRI using Developed Model (m/km)
Sikar –Jaipur (NH-11) (left wheel Path)	1	17/00	170	2.85	0.45	0.29
	2	17/50	206	2.71	0.31	0.35
	3	17/100	184	2.79	0.39	0.31
	4	17/150	200	2.76	0.36	0.34
	5	17/200	172	2.90	0.50	0.29
	6	17/250	220	2.70	0.30	0.37
	7	17/300	240	2.73	0.33	0.41
	8	17/350	292	2.80	0.40	0.50
	9	17/400	190	2.89	0.49	0.32
	10	17/450	268	2.90	0.50	0.46
	11	17/500	300	3.03	0.63	0.51
	12	17/550	240	3.00	0.60	0.41
	13	17/600	192	2.98	0.58	0.33
	14	17/650	200	3.00	0.60	0.34
	15	17/700	320	2.77	0.37	0.54
	16	17/750	240	2.78	0.38	0.41
	17	17/800	228	2.81	0.41	0.39
	18	17/850	240	3.04	0.64	0.41
	19	17/900	270	3.06	0.66	0.46
	20	17/950	216	3.01	0.61	0.37

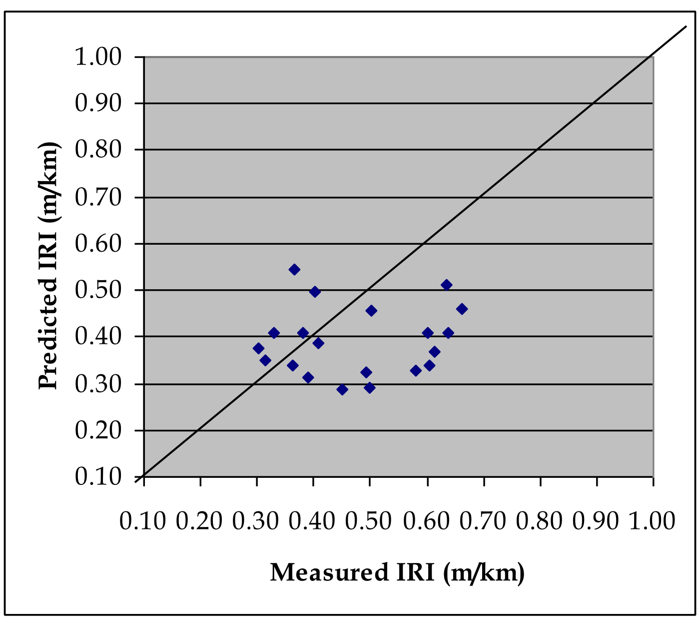


Fig 5.14: Plot between Measured and Predicted IRI on Rutted Pavement Surface

5.5.2 Prediction of IRI from Raveling

To find the contribution of raveling on the overall roughness, pavement surface of length one km on Sikar-Jaipur National Highway was selected where such type of distress was predominant and other kind of distresses were not observed during visual inspection. This stretch was divided into 20 uniform sections of length 50m each and raveling presents in low and medium severity were collected. Roughness data was also collected on that stretch using Bump Integrator running at 32 km/hr. Data collected on this stretch has been presented in Table 5.8. As this stretch is on NH-11, hence the initial roughness value of 2.4 m/km was deducted and remaining value was compared with the roughness predicted using the developed model.

Table 5.8: Measured and Predicted IRI on Raveled Pavement Surface

Name and Type of the Road	Section No.	Chainage	RL	RM	Measured IRI (m/km)	(IRI-Initial IRI) (m/km)	Predicted IRI using developed Model (m/km)
Siker – Jaipur (NH-11)	1	23.00	84.5	15.5	3.95	1.55	1.59
	2	23/50	68	32	4.35	1.95	1.71
	3	23/100	73.2	26.5	4.01	1.61	1.66
	4	23/150	92.4	7.6	4.07	1.67	1.53
	5	23/200	79	21	4.24	1.84	1.63
	6	23/250	78.4	21.6	4.12	1.72	1.63
	7	23/300	86	14	4.07	1.67	1.58
	8	23/350	80	20	4.12	1.72	1.62
	9	23/400	89.3	10.7	3.89	1.49	1.56
	10	23/450	100	0	4.09	1.69	1.48
	11	23/500	90	10	3.97	1.57	1.55
	12	23/550	95	4.6	3.82	1.42	1.51
	13	23/600	71.3	27.7	4.22	1.82	1.66
	14	23/650	56.2	43.8	4.39	1.99	1.79
	15	23/700	100	0	3.95	1.55	1.48
	16	23/750	100	0	3.87	1.47	1.48
	17	23/800	61.4	38.6	4.09	1.69	1.75
	18	23/850	69	31	3.99	1.59	1.70
	19	23/900	71.5	28.5	4.37	1.97	1.68
	20	23/950	88	12	4.18	1.78	1.57

A graph shown in Fig 5.15 was also plotted to see the deviation of measured and predicted values with ideal line.

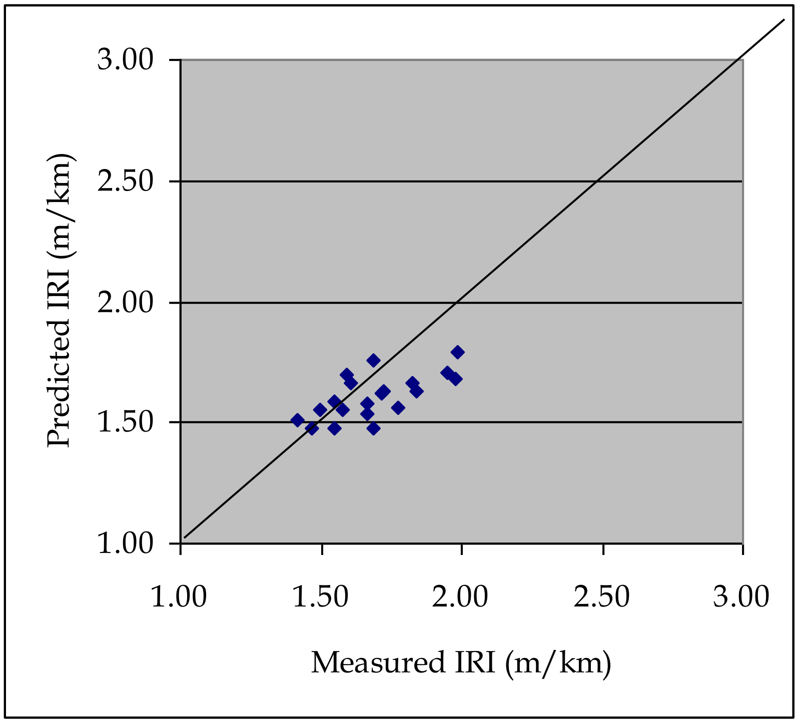


Fig 5.15: Plot between Measured and Predicted IRI on Raveled Pavement Surface

The graph and the table show that in most of the points the difference was very low and some other points have minor variations. This might be due to the fact that though the stretches were selected where the rutting was predominant, the possibility of other distresses, though minor in quality influencing the roughness could not be ruled out. This might have caused the variation in predicted and observed values.

5.6 PREDICTION OF CHANGE IN ROUGHNESS LEVELS DUE TO MAINTENANCE ACTIVITY

To study the changes in IRI values due to a selected maintenance work, investigation was carried out on a chosen stretch of one km over a MDR (Pilani-Loharu, Chainage is 3/000 to 4/000 km) where the various types of distresses are present. This stretch was divided into 20 uniform sections of 50 m each. On these sections all the distress parameters were noted in terms of severity and extent and roughness was found (Table 5.9). Coincidently as a part of routine maintenance work local Public Works Department (PWD) repaired only the potholes with manual patch work on this stretch. On inspection it was observed that a level difference exists between the patched surface and pavement surface due to improper compaction. Thus, it was decided to wait for about one and half months to allow compaction of the patched surface due to traffic. Afterwards once again pavement roughness data was collected to find the improvement of roughness values. Though the potholes were repaired, it resulted in low level patching failure due to unsound patching practice usually adopted at local level. Hence, the total patched area was considered as low level patching while the pothole being removed (Table 5.10). The new roughness of the road stretch was then calculated using the roughness model developed in this study. It may be noted here that the selected stretch was on MDR and hence, the initial roughness of 3.0 m/km was deducted from the measured roughness as discussed in article 5.4.2 to find the roughness due to distresses only. The relationships between observed and predicted IRI values between before and after patching have been shown in Fig 5.16. Examination of the figure shows very close correlation, thus establishing the suitability of using the model for predicting the impact of selected maintenance work on IRI.

Table 5.9: Pavement Condition and Roughness data on a Selected Section before the Maintenance

Section No.	RL	RM	RH	PAL	PAM	PAH	PL	PM	PH	CL	CM	CH	RUL	Measured IRI (m/km)	IRI-Initial IRI (m/km)	Predicted IRI using developed Model (m/km
1	33.74	7.99	8.33	8.60	18.33	0.00	2.79	9.21	1.00	10.00	0.00	0.00	0	6.29	3.29	3.87
2	21.70	19.75	0.00	0.00	18.33	0.00	9.11	0.27	0.25	10.00	10.58	10.00	160	6.38	3.38	3.49
3	30.11	50.80	9.75	4.20	0.00	0.00	2.08	0.96	2.10	0.00	0.00	0.00	160	6.13	3.13	3.00
4	27.00	10.00	27.55	18.80	6.80	0.00	1.30	0.75	7.80	0.00	0.00	0.00	140	7.08	4.08	4.19
5	0.00	25.60	42.50	2.70	22.15	0.00	0.25	3.00	3.80	0.00	0.00	0.00	80	7.39	4.39	4.24
6	21.33	42.20	26.50	1.20	0.00	0.00	4.47	1.00	3.30	0.00	0.00	0.00	0	6.35	3.35	3.35
7	28.00	27.00	20.83	2.00	17.50	0.00	3.33	0.58	0.75	0.00	0.00	0.00	0	6.13	3.13	3.09
8	35.53	0.00	32.11	21.62	6.30	0.00	1.55	1.54	1.36	0.00	0.00	0.00	200	6.82	3.82	3.5
9	28.52	22.08	11.71	0.00	25.67	0.00	1.33	2.42	8.27	0.00	0.00	0.00	0	6.55	3.55	4.23
10	37.36	17.41	13.46	0.00	8.00	0.00	0.00	8.28	15.49	0.00	0.00	0.00	0	8.62	5.62	5.41
11	26.19	19.50	17.50	25.75	2.00	0.00	5.23	2.63	1.20	0.00	0.00	0.00	120	6.37	3.37	3.63
12	34.18	4.00	20.00	14.30	0.00	0.00	4.17	13.83	9.53	0.00	0.00	0.00	0	7.77	4.77	5.65
13	48.15	0.00	19.17	22.50	0.00	0.00	0.00	9.60	0.58	0.00	0.00	0.00	0	5.36	2.36	3.49
14	40.58	8.00	17.33	0.00	0.00	0.00	20.00	3.50	8.58	2.00	0.00	0.00	0	7.94	4.94	5.46
15	36.29	22.33	0.00	16.67	0.00	0.00	0.88	6.90	8.93	8.00	0.00	0.00	80	7.27	4.27	4.28
16	57.99	16.00	0.00	13.96	0.00	0.00	0.38	1.47	0.21	10.00	0.00	0.00	140	5.18	2.18	2.27
17	33.19	21.10	13.68	0.00	0.00	0.00	1.40	4.82	9.82	6.00	10.00	0.00	0	6.64	3.64	4.09
18	41.58	37.50	10.75	0.00	0.00	0.00	0.00	0.63	1.54	5.00	3.00	0.00	0	5.15	2.15	2.25
19	32.11	8.00	16.67	15.83	0.00	0.00	0.60	1.20	0.42	16.00	9.17	0.00	0	5.39	2.39	2.35
20	25.15	10.00	17.00	33.63	0.00	0.00	0.69	11.43	1.10	0.00	1.00	0.00	0	7.38	4.38	4.07

LEGEND: CL=Low level cracking CM=Medium level cracking CH =High level cracking PL=Low level potholes PM=Medium level pothole PH =High level potholes RL=Low level raveling RM=Medium level raveling RH=High level raveling PAL=Low level patching PAM=Medium level patching PAH=High level patching RUL=Low level rutting RUM=Medium level rutting RUH=High level rutting

Table 5.10: Pavement Condition and Roughness data on a Selected Section after the Maintenance Activity

Section No.	RL	RM	RH	PAL	PAM	PAH	PL	PM	PH	CL	CM	CH	RUL	Measured IRI (m/km)	IRI-Initial IRI (m/km)	Predicted IRI using developed Model (m/km
1	33.74	7.99	8.33	21.60	18.33	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0	5.48	2.48	2.52
2	21.70	19.75	0.00	9.63	18.33	0.00	0.00	0.00	0.00	10.00	10.58	10.00	160	5.31	2.31	2.71
3	30.11	50.80	9.75	9.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	160	5.1	2.1	2.45
4	27.00	10.00	27.55	28.65	6.80	0.00	0.00	0.00	0.00	0.00	0.00	0.00	140	6.03	3.03	2.97
5	0.00	25.60	42.50	9.75	22.15	0.00	0.00	0.00	0.00	0.00	0.00	0.00	80	5.88	2.88	3.4
6	21.33	42.20	26.50	9.97	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	5.51	2.51	2.45
7	28.00	27.00	20.83	6.67	17.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	5.86	2.86	2.67
8	35.53	0.00	32.11	26.07	6.30	0.00	0.00	0.00	0.00	0.00	0.00	0.00	200	6.23	3.23	3.04
9	28.52	22.08	11.71	12.02	25.67	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	5.4	2.4	2.77
10	37.36	17.41	13.46	23.77	8.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	5.39	2.39	2.47
11	26.19	19.50	17.50	34.81	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	120	5.68	2.68	2.77
12	34.18	4.00	20.00	41.83	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	5.58	2.58	2.56
13	48.15	0.00	19.17	32.68	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0	5.67	2.67	2.37
14	40.58	8.00	17.33	32.08	0.00	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0	5.3	2.3	2.38
15	36.29	22.33	0.00	33.38	0.00	0.00	0.00	0.00	0.00	8.00	0.00	0.00	80	4.84	1.84	2.28
16	57.99	16.00	0.00	16.01	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00	140	5.11	2.11	2.05
17	33.19	21.10	13.68	16.03	0.00	0.00	0.00	0.00	0.00	6.00	10.00	0.00	0	4.93	1.93	2.16
18	41.58	37.50	10.75	2.17	0.00	0.00	0.00	0.00	0.00	5.00	3.00	0.00	0	4.81	1.81	1.98
19	32.11	8.00	16.67	18.05	0.00	0.00	0.00	0.00	0.00	16.00	9.17	0.00	0	5.07	2.07	2.12
20	25.15	10.00	17.00	46.85	0.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	0	5.31	2.31	2.63

LEGEND: CL=Low level cracking CM=Medium level cracking CH =High level cracking PL=Low level potholes PM=Medium level pothole PH =High level potholes RL=Low level raveling RM=Medium level raveling RH=High level raveling PAL=Low level patching PAM=Medium level patching PAH=High level patching RUL=Low level rutting RUM=Medium level rutting RUH=High level rutting

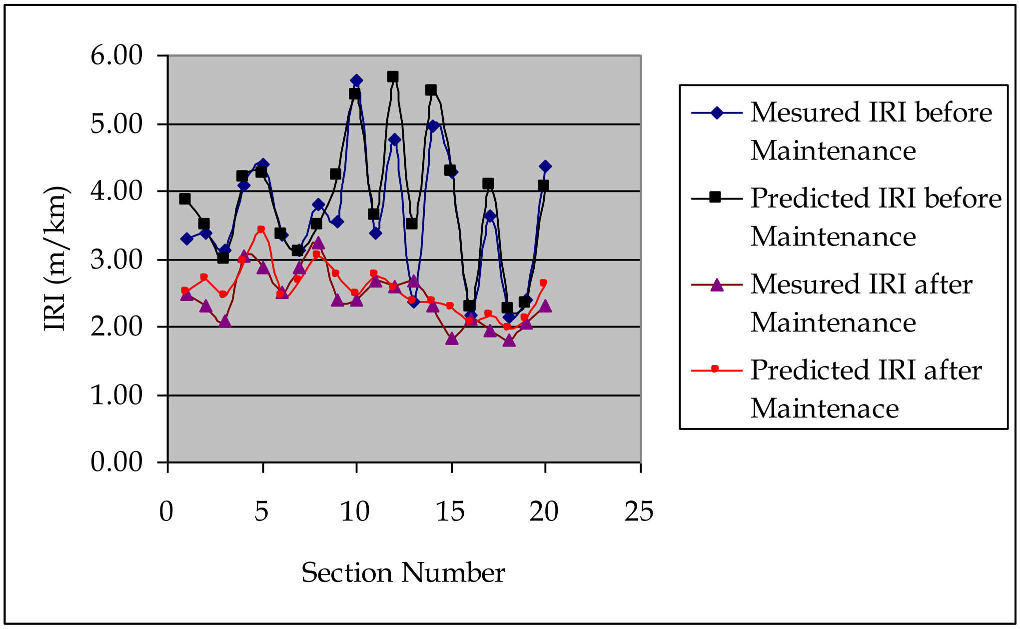


Fig 5.16: Change in Roughness Values due to Maintenance

5.7 APPLICABILITY OF ROUGHNESS MODEL WITH THE PAVEMENT DISTRESSES AND IRI DATA COLLECTED OVER ENTIRE WIDTH OF THE PAVEMENT

One of the objectives of this study was to determine the effect of carrying out selected maintenance activities on the roughness of a pavement stretch. The roughness model developed in this study was based on the data collected over the defined wheel path. However, it is common practice to collect the pavement distresses data over the entire width of the pavement for taking maintenance decisions. Hence, it was decided to check the applicability of developed model with the distresses and roughness data collected over the entire width of the pavement and accordingly, the relevant data was collected as discussed in section 5.5. The roughness data was collected in 14 strips and the average value was considered as the IRI of the pavement stretch. This value was used for comparing the roughness predicted from the pavement distresses obtained using Eq. 5.7. The data collected over 20 sections of 50 m length on Major District Road (MDR), State Highway (SH), and National Highway (NH) as discussed in section 4.5 was used for validation.

Roughness data collected on 14 different strips over the entire width on selected 20 pavement sections on different functional classes of highways (MDR, SH, NH) have been exhibited in Fig. 5.17 to Fig. 5.19. In the figures wheel path number one presents the path 10 cm away (due to difficulty in running Bump Integrator while collecting the roughness 10 cm along edge was left out) from the edge of the pavement.

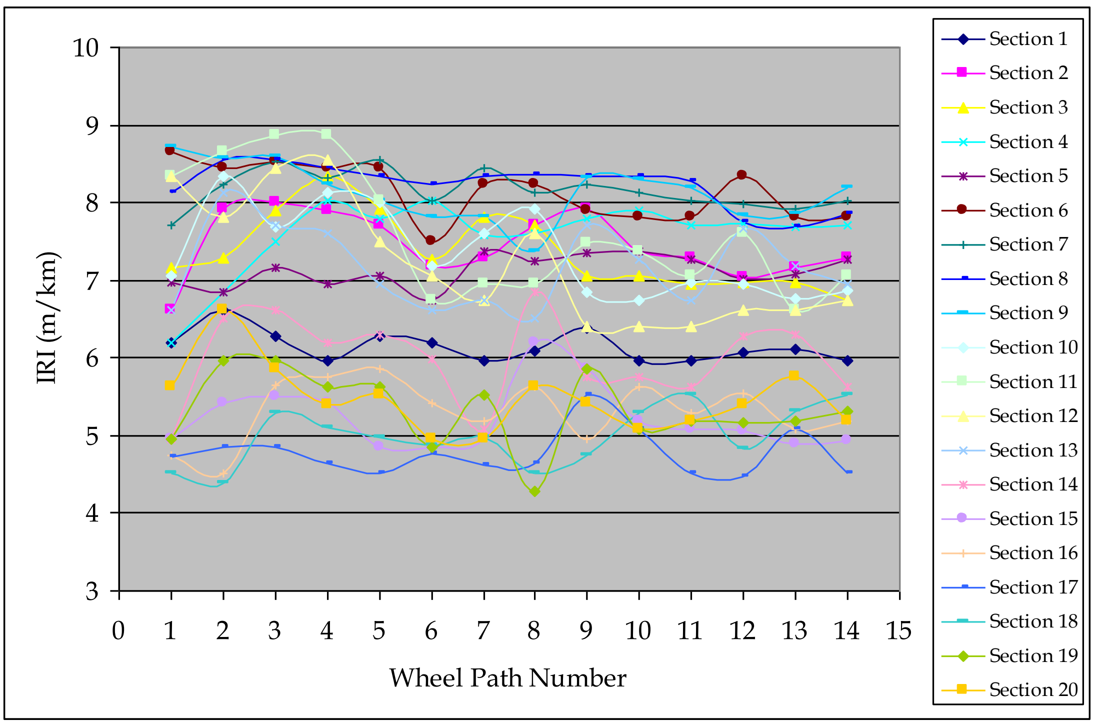


Fig. 5.17: Roughness on Different Strips over Entire Width on MDR

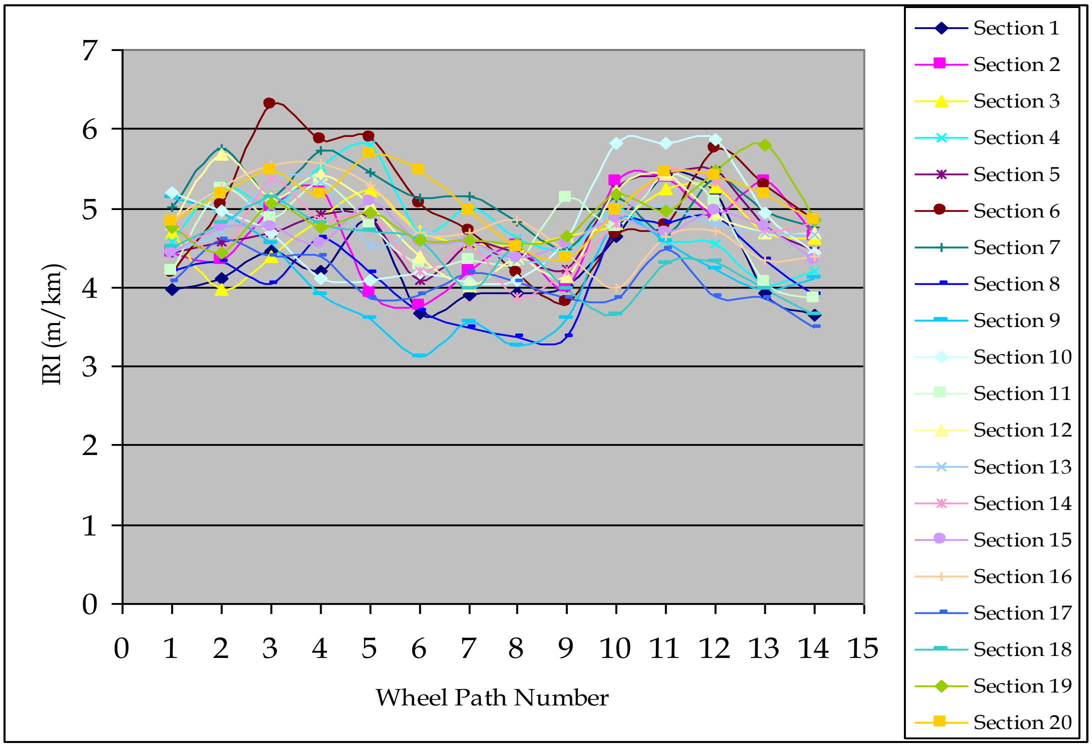


Fig. 5.18: Roughness on Different Strips Over Entire Width on SH

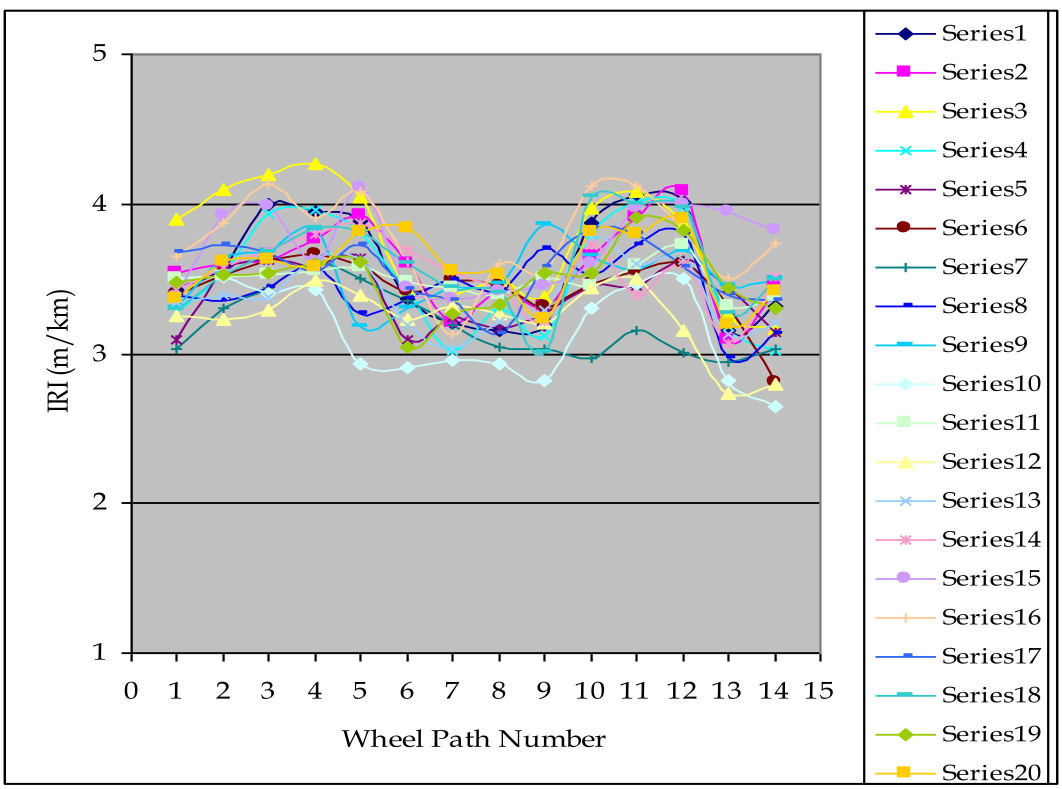


Fig. 5.19: Roughness on Different Strips over Entire Width on NH

It may be observed from Fig 5.17 that the stretches selected for the study on MDR had substantial variations in IRI values. This shows that the selection of the stretches was appropriate in representing different service condition of roads. However, there was not much variation in roughness values on different strips along the transverse direction in any section. The reason may be attributed to the fact that, on the observed stretches the wheel paths were not properly defined in the absence of centre line markings, thus, the number of wheel load repetitions was almost similar over the entire width of the pavement. Also in the absence of high traffic volume the drivers of the vehicles had freedom to chose the path of travel and thus prominent wheel paths were not found.

The SHs are usually better maintained as compared to MDRs and thus the variation of IRI was not high among the stretches as shown in Fig 5.18. The roughness was slightly higher at a distance 34 cm to 106 cm from the edge of the pavement and 24 cm to 96 cm from the centre line of the road as compared to other locations over transverse direction in all the pavement stretches. It may be attributed to the fact that, number of wheel load repetitions was along a path. This was because the vehicles usually follow a wheel path in the presence of centerline marking.

The NHs are usually maintained properly and the quality of construction is good and thus IRI values obtained are low as compared to those of SHs and MDRs. All the stretches are showing wheel path clearly (Fig 5.19). The roughness is moderately high at a distance 58 cm to 106 cm from the edge of the pavement and 48 cm to 96 cm from the center line. It is due to the channnelization of traffic in the presence of proper markings and high traffic volume in both the directions. Thus the vehicle is forced to a certain wheel path.

To compare the predicted and measured IRI, the data collected over entire width on 20 sections of 50 m each on MDR was taken for sample calculation (Table 5.11). This was done because the IRI values varied widely. This table shows the magnitudes of 15 distress parameters for each section along with the average measured and predicted IRI. However, in some of the stretches all the distress parameters were not present and the high severity rutting was not observed in any of the sections. The average roughness of the selected sections presented in the Table 5.11 was calculated from the roughness value collected on different strips over the entire width of the pavement (Table 4.12). These sections were on MDR, hence, an initial roughness of 3.0 m/km was deducted from the measured roughness as discussed in section 5.4.2. Predicted IRI was obtained by substituting the pavement distresses in Eq. 5.7. The same procedure was followed to predict the roughness on the sections selected over SH and NH.

To validate the predicted IRI, plots were being drawn between measured average IRI from the different strips as ordinates and predicted IRI as abscissa. The plots for stretches selected on MDR, SH and NH have been shown in Fig 5.20 to Fig 5.22 respectively. A 45^0 line has been drawn to see the distribution of plotted points on either side of an ideal line.

It can be observed from the figures 5.20 to 5.22 that, majority of the points fell either close or on the ideal line. It shows that there is an acceptable variation between the measured and predicted values. Though the roughness measured over entire width of the pavement have little variation on few strips on SH and NH, not affecting the results, because average IRI was used for comparison. Thus it may be concluded that the roughness value predicted from the distress parameters collected over entire width of the pavement is more or less equal to the average value calculated from the different strips.

Table 5.11: Predicting the IRI Values from Pavement Distress Parameters Collected Over the Entire Stretch of Road

Section No.	RL	RM	RH	PAL	PAM	PAH	PL	PM	PH	CL	CM	CH	RUL	RUM	RUH	Measured Average IRI (m/km)	Roughness due to distress (m/km)	Predicted IRI using developed Model (m/km)
1	2.5	10	45.4	3.2	26.9	10.1	0.6	0.9	0	0	0	0	0	0	0	6.15	3.15	3.69
2	5.1	11.1	30	11.2	35.6	0	2.3	3.3	1.2	0	0	0	200	0	0	7.46	4.46	4.45
3	24	20	1.4	14.2	3.4	21.7	4.5	2.1	4.2	3.7	0	0	120	0	0	7.37	4.37	4.08
4	16	10	30	0	15.5	6.2	2.3	2.3	4.1	10	0	0	90	200	0	7.58	4.58	4.40
5	17.4	10	56	0	1.7	0	3.7	5.2	0.2	2	2	0	0	0	0	7.16	4.16	3.69
6	0	7	42	0	0	3.2	5.5	4.1	5.8	18	14	0	120	180	0	8.14	5.14	4.94
7	3	17.4	48.6	0	0	11.2	3.6	6.1	8.3	0	0	0	60	0	0	8.16	5.16	5.28
8	0	20.2	28.9	0	11.2	22.3	6.8	7.2	3.3	0	0	0	120	120	0	8.23	5.23	5.66
9	0	41	26	0	18	3.4	2.3	6.8	1.9	0	0	0	200	120	0	8.13	5.13	4.84
10	0	24.6	54	0	0.1	4	0.3	0.9	1.9	0	0	0	160	240	0	7.36	4.36	3.89
11	0	43.1	5.7	0	0	6.8	4.6	9.5	4.3	14.4	0	0	0	0	0	7.62	4.62	4.12
12	2	0	38	6	24.9	15	0.3	1.4	1.1	0	0	0	60	0	0	7.23	4.23	3.74
13	0	12.3	32	0	0.9	0	8.2	11.9	4.5	0	0	0	0	0	0	7.17	4.17	4.69
14	10.4	58	8	0	4	0	4.4	5.1	0.9	0	0	0	100	0	0	5.99	2.99	3.37
15	34	14	17.1	20	0	0	0.2	1.3	0	0	0	0	0	220	0	5.23	2.23	2.74
16	30	22	14	18	0	0	0.3	0.8	3.6	0	0	0	180	0	0	5.32	2.32	3.00
17	96	0	0	0	0	0	0	0	0	2	0	0.4	280	220	0	4.77	1.77	2.46
18	70	16.1	6.1	0	0	0	0.1	0.7	1.8	0	0	0	0	200	0	4.99	1.99	2.48
19	86.2	0	0	0	6	0	0.3	0.1	0	4	0	0	140	180	0	5.33	2.33	2.29
20	48	9	0	0.1	14.2	0	2.6	0.7	2.3	4	0	0	0	0	0	5.47	2.47	2.31

LEGEND: CL=Low level cracking CM=Medium level cracking CH =High level cracking PL=Low level potholes PM=Medium level pothole PH =High level potholes RL=Low level raveling RM=Medium level raveling RH=High level raveling PAL=Low level patching PAM=Medium level patching PAH=High level patching RUL=Low level rutting RUM=Medium level rutting RUH=High level rutting

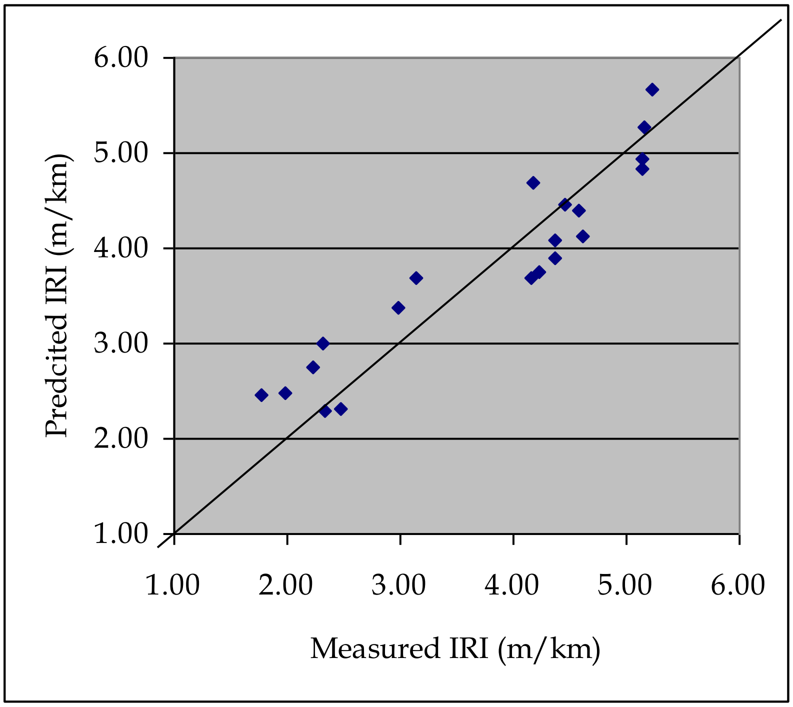


Fig 5.20: Plot between Measured Average IRI and Predicted IRI from the Distress Parameters Collected Over Entire Width of the Pavement on MDR

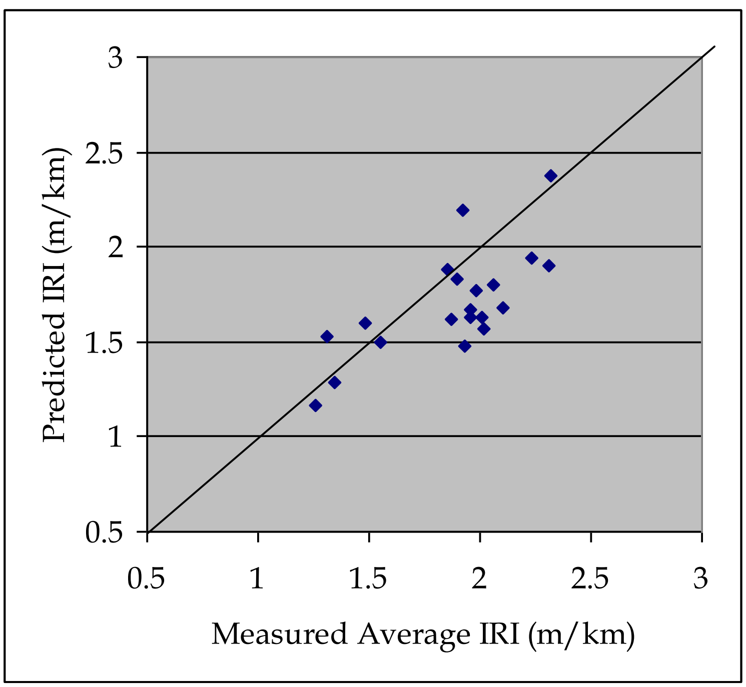


Fig 5.21: Plot between Measured Average IRI and Predicted IRI from the Distress Parameters Collected Over Entire Width of the Pavement on SH

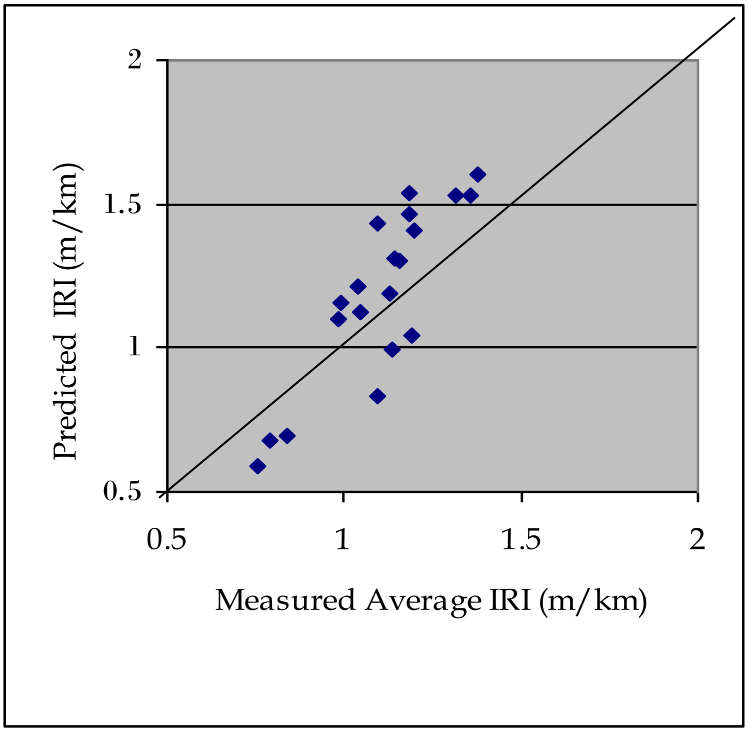


Fig 5.22: Plot between Measured Average IRI and Predicted IRI from the Distress Parameters Collected Over Entire Width of the Pavement on NH

5.8 SUMMARY

In this Chapter, models were for calibration of Bump Integrator used for the roughness measurement and its standardization at different operating speeds. Development and validation of pavement roughness model to predict the IRI from the pavement distress parameters at a given point of time was discussed in detail. Roughness prediction capability of developed model from the individual distress parameters and changes in IRI levels due to maintenance activities was also presented. Finally, the developed model was validated with the data collected over entire width of the pavement.

CHAPTER 6

PRIORITIZATION AND GROUPING OF PAVEMENT STRETCHES FOR MAINTENANCE

6.1 BACKGROUND

Besides construction of new highways and road links, proper upkeep of the existing pavements is essential for the economic growth of any country. Inadequate and inappropriate maintenance policies result in heavy financial losses in the form of ever increasing Road User Cost (RUC).

With the rapid increase in the road construction activities in the Less Developed Countries including India, the total funds required for pavement maintenance is continuously increasing. But it is difficult to get adequate funding for maintaining all the roads in a network in good condition. Thus, there is a need to develop an effective and methodical system for maintaining the entire road network in a specified area to the desired serviceability level with the available funds.

Pavement Maintenance System (PMS) is an ideal tool in this kind of situation and offers a methodical way of up keeping the road network in its best possible serviceability level. In any PMS, prioritization of road stretches according to their condition plays a major role especially when the funds available for road maintenance are limited (Fwa et al., 1994; Alsugair and Al-Qudrah, 1998; Reddy and Veeraragavan, 2002). A number of researchers have developed various prioritization techniques, to rank the road stretches in a network. They are based on the pavement distresses data collected through visual observations. Different distresses and their extent would have different impacts on the pavement condition and thus their weights need to be determined to prioritize the stretches. But these weights are subjective in nature and thus there would be uncertainty and ambiguity in assessing them. In such uncertain situations, Fuzzy Multi-Criteria Decision Making (FMCDM) approach provides an ideal option and it has been tried and tested by number of researchers for prioritizing alternatives in different situations as discussed in literature. Hence, in this study the fuzzy approach has been used for prioritizing the pavement stretches.

While dealing with a large number of stretches and practical difficulties while carrying the maintenance operations as per rank wise, it is always useful to classify them into a manageable number of groups, so that the prioritization could be done group wise instead of stretch wise.

6.2 PRIORITIZATION OF PAVEMENT STRETCHES

Distresses data collected over entire width of the pavement have been used for prioritizing the stretches. As discussed in the earlier section, due to presence of ambiguity in assessing the weights of the distress parameters, fuzzy approach would be ideal for prioritizing the pavement stretches. Number of researchers have used fuzzy for prioritizing the alternatives but not much literature is available on its application in the area of pavement maintenance. Bandara & Gunaratne (2001) have used fuzzy approach for the prioritization of the road stretches. They assumed that ambiguity is involved in measuring the extent of distresses and their weights. Accordingly fuzzy approach was used for assessing extent and weights of distresses. However, fuzzy approach has to be applied only when uncertainty is predominant. In other words, when particular parameter is quantifiable with fair degree of accuracy, this approach need not be used. Hence, it was felt in this study that the extent of distress could be measured fairly accurately in the field and thus there was no need to incorporate fuzzy theory in measuring them. Since less number of studies has been reported on the contribution of each distress on the overall pavement condition and the uncertainty and ambiguity presents in assessing them, it was decided to apply fuzzy theory in determining them.

6.2.1 Brief Introduction to Fuzzy Logic

The theory of fuzzy sets was first proposed by Zadeh in 1965. A fuzzy set is a class of elements or objects without any definite boundaries between them. The fuzzy logic is useful to define the real world objects which are characterized by vagueness and uncertainty. It is a multivalued theory wherein intermediate values such as "moderate", "high", "low" are used to define a condition instead of yes or no, true or false as in the case of conventional crisp theory. The fuzzy sets are defined by the membership functions. If a fuzzy number $\tilde{A}$ is a fuzzy set, and its membership function is $\mu_{\tilde{A}}(x)$: R → [0, 1] (Chen, 1997; Chan et al., 1999), where *'x'* represents the criteria. Generally, linear membership function is widely used and the corresponding fuzzy numbers are called Triangular Fuzzy Numbers (TFNs), whose membership is defined by three real numbers *(l, m, n),* which is pictorially shown in Fig. 6.1.

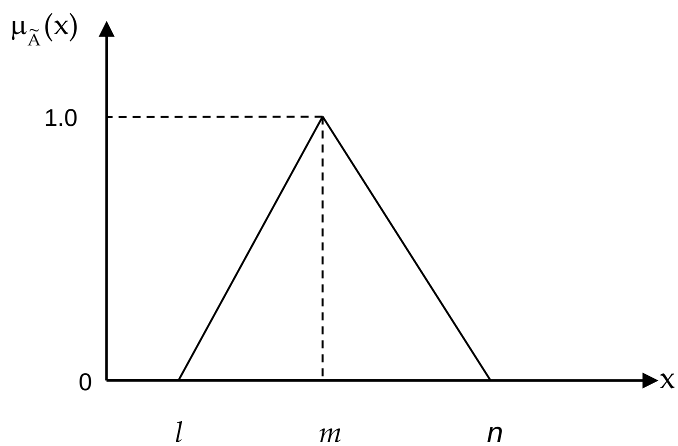


Fig 6.1: Membership Function for the Triangular Fuzzy Numbers

In Fig. 6.1, m is the most possible value of a fuzzy number $\tilde{A}$, and l and n are the lower and upper bounds respectively. The TFNs can be expressed as follows.

$$\mu_{\tilde{A}}(x) = \begin{cases} \dfrac{(x-l)}{(m-l)}; & l \leq x \leq m; \\ \dfrac{(n-x)}{(n-m)}; & m \leq x \leq n; \\ 0; & \text{Otherwise}; \end{cases} \qquad (5.1)$$

6.2.1.1 Operations on fuzzy numbers

Let $\tilde{A} = (l, m, n)$ and $\tilde{B} = (p, q, r)$ two TFNs, the general operations are as follows (Prakash, 2003).

- Addition of two fuzzy number
  $(l, m, n) \oplus (p, q, r) = (l + p, m + q, n + r)$

- Subtraction of two fuzzy numbers
  $(l, m, n) \Theta (p, q, r) = (l - r, m - q, n - p)$

- Multiplication of any real number "k" and a fuzzy number
  $k \otimes (l, m, n) = (kl, km, kn)$

- Division of any fuzzy number real and a number "k"
  $(l, m, n) \div k = (\frac{l}{k}, \frac{m}{k}, \frac{n}{k})$

Where the symbols $\oplus, \Theta, \otimes$ represents fuzzy addition, fuzzy subtraction and fuzzy multiplication respectively.

6.2.2 Prioritization Process

Pavement condition data collected on 20 sections of length 50 m each presented in Table 4.4 is being used for explaining the prioritization process. Three different approaches have been tried and then compared as discussed in detail in the following sections.

6.2.2.1 Prioritization of pavement sections as per approach I

In approach-I, pavement sections have been prioritized based on the method proposed by various researchers such as Bandara and Gunaratne (2001); Chen-Tung Chen (2001); Huang (1989). The stages involved in the prioritization process has been discussed below.

Stage 1: Pavement distresses data presented in Table 4.4 was normalized in the scale of 0 to 100 with respect to the maximum value in the series through a simple normalization using equation 6.2. A summary of normalization data has been presented in Table 6.1.

$$\text{Normalized value} = \frac{x_{ji}}{\max(x_{ji})} * 100 \qquad (6.2)$$

Where,

x_{ji} is the extent of a criteria C_j of pavement section A_i

Max (x_{ji}) is the maximum extent value of a criteria C_j of pavement section A_i

Stage 2: These normalized values thus obtained were arranged into 10 groups with a uniform interval of 10 (Table 6.2) and accordingly ratings were given to all the normalized values. For example, the normalization value of high severity potholes (PH) on section No. 9 is 23.51 (Table 6.1) and is rated 3 (Table 6.2).

Table 6.1: Normalized Pavement Condition data on Selected Stretch

Section No.	Criteria																	
	CL	CM	CH	PL	PM	PH	RL	RM	RH	PAL	PAM	PAH	RUL	RUM	RUH	EL	EM	EH
A_{1}	0.00	0.00	0.00	5.85	2.86	0.00	2.57	17.26	82.98	16.00	100.0	67.35	20.83	0.00	0.00	45.50	0.00	0.00
A_{2}	0.00	0.00	0.00	2.63	3.42	0.00	37.57	53.56	7.49	55.89	58.12	0.00	0.00	58.82	0.00	36.50	0.00	0.00
A_{3}	6.59	0.00	0.00	14.31	0.47	0.00	56.25	34.48	2.65	0.00	12.74	11.43	0.00	0.00	0.00	0.00	0.00	0.00
A_{4}	100.0	0.00	0.00	3.06	0.00	0.00	52.08	17.24	0.00	0.00	0.00	0.00	37.50	0.00	100.0	16.67	0.00	0.00
A_{5}	7.69	14.29	0.00	6.88	2.31	2.56	58.33	17.24	48.15	0.00	6.37	0.00	41.67	70.59	0.00	33.33	0.00	0.00
A_{6}	69.23	100.0	0.00	4.89	0.19	0.00	50.00	31.03	0.00	0.00	0.00	0.00	33.33	0.00	0.00	10.00	0.00	0.00
A_{7}	0.00	0.00	0.00	2.78	6.99	4.28	20.83	86.21	33.33	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A_{8}	0.00	0.00	0.00	1.39	0.67	16.39	0.00	34.84	53.47	0.00	42.46	0.00	75.00	70.59	100.0	100.0	0.00	0.00
A_{9}	0.00	0.00	0.00	0.00	0.00	23.51	0.00	82.76	48.15	0.00	66.88	0.00	91.67	94.12	55.56	11.67	0.00	0.00
A_{10}	0.00	0.00	0.00	2.78	2.80	22.88	0.00	42.36	100.0	0.00	0.21	26.67	0.00	0.00	0.00	0.00	0.00	0.00
A_{11}	0.00	0.00	0.00	100	100	100	0.00	74.38	0.00	0.00	11.15	0.00	50.00	0.00	0.00	0.00	0.00	0.00
A_{12}	0.00	0.00	0.00	3.33	4.64	13.26	2.08	0.00	70.37	30.00	92.36	100.0	0.00	0.00	0.00	0.00	0.00	0.00
A_{13}	0.00	0.00	0.00	24.50	38.71	20.35	0.00	21.18	59.26	0.00	3.18	0.00	100.0	100.0	88.89	0.00	73.33	72.92
A_{14}	0.00	0.00	0.00	8.33	9.06	39.37	0.00	100	14.81	0.00	14.86	0.00	0.00	0.00	0.00	25.00	30.00	0.00
A_{15}	0.00	0.00	0.00	1.67	4.38	61.96	14.58	24.14	68.78	100.0	0.00	0.00	41.67	0.00	0.00	26.67	0.00	100.0
A_{16}	0.00	0.00	0.00	2.56	2.57	44.56	31.25	37.93	25.93	90.00	0.00	0.00	66.67	35.29	22.22	33.33	100.0	0.00
A_{17}	7.69	0.00	0.00	4.17	0.00	0.00	100	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A_{18}	0.00	0.00	0.00	0.89	2.39	21.61	72.92	27.83	11.38	0.00	0.00	0.00	54.17	29.41	44.44	0.00	0.00	0.00
A_{19}	15.38	0.00	0.00	3.00	0.47	0.00	89.76	0.00	0.00	0.00	22.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00
A_{20}	15.38	0.00	0.00	5.56	2.33	0.00	70.83	15.52	0.00	0.71	52.78	0.00	87.50	0.00	0.00	0.00	0.00	0.00

LEGEND: CL=Low level cracking CM=Medium level cracking CH =High level cracking PL=Low level potholes PM=Medium level pothole PH =High level potholes RL=Low level raveling RM=Medium level raveling RH=High level raveling PAL=Low level patching PAM=Medium level patching PAH=High level patching RUL=Low level rutting RUM=Medium level rutting RUH=High level rutting EL=Low level edge failure EM=Medium level edge failure EH=High level edge failure

Table 6.2: Ratings for the Normalized Values

Normalized Value	0-10	11-20	21-30	31-40	41-50	51-60	61-70	71-80	81-90	91-100
Rating	1	2	3	4	5	6	7	8	9	10

Stage 3: The ratings were then arranged in a matrix form, named as Rating Matrix $(R_{ij})_{N\times M}$ as shown in Eq 6.3. In this equation each row represents pavement sections (A_1, A_2……., A_N) and each column represents criteria or distress parameter.

$$(R_{ij})_{N\times M} = \begin{bmatrix} R_{11} & R_{12} & \cdots & R_{1M} \\ R_{21} & R_{22} & \cdots & R_{2M} \\ \vdots & \vdots & \cdots & \vdots \\ R_{N1} & R_{N2} & \cdots & R_{NM} \end{bmatrix} \tag{6.3}$$

Where,

R_{ij} is the real number for the pavement section A_i and criteria C_j

M is the toal number of criteria and N is Number of stretches

The Rating Matrix was then prepared for the example problem using Table 6.1 and 6.2 and is shown in Table 6.3.

Table 6.3: Rating Matrix

$$[R_{ij}]_{N\times M} = \begin{array}{c} \begin{array}{cccccccccccccccccc} C_1 & C_2 & C_3 & C_4 & C_5 & C_6 & C_7 & C_8 & C_9 & C_{10} & C_{11} & C_{12} & C_{13} & C_{14} & C_{15} & C_{16} & C_{17} & C_{18} \end{array} \\ \left[\begin{array}{cccccccccccccccccc}
1 & 1 & 1 & 1 & 1 & 1 & 1 & 2 & 9 & 2 & 10 & 7 & 3 & 1 & 1 & 5 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 4 & 6 & 1 & 6 & 6 & 1 & 1 & 6 & 1 & 4 & 1 & 1 \\
1 & 1 & 1 & 2 & 1 & 1 & 6 & 4 & 1 & 1 & 2 & 2 & 1 & 1 & 1 & 1 & 1 & 1 \\
10 & 1 & 1 & 1 & 1 & 1 & 6 & 2 & 1 & 1 & 1 & 1 & 4 & 1 & 10 & 2 & 1 & 1 \\
1 & 2 & 1 & 1 & 1 & 1 & 6 & 2 & 5 & 1 & 1 & 1 & 5 & 8 & 1 & 4 & 1 & 1 \\
7 & 10 & 1 & 1 & 1 & 1 & 6 & 4 & 1 & 1 & 1 & 1 & 4 & 1 & 1 & 2 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 3 & 9 & 4 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 2 & 1 & 4 & 6 & 1 & 5 & 1 & 8 & 8 & 10 & 10 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 3 & 1 & 9 & 5 & 1 & 7 & 1 & 10 & 10 & 6 & 2 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 3 & 1 & 5 & 10 & 1 & 1 & 3 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 10 & 10 & 10 & 1 & 8 & 1 & 1 & 2 & 1 & 6 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 2 & 1 & 1 & 8 & 4 & 10 & 10 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 3 & 4 & 3 & 1 & 3 & 6 & 1 & 1 & 1 & 10 & 10 & 9 & 1 & 8 & 8 \\
1 & 1 & 1 & 1 & 1 & 4 & 1 & 10 & 2 & 1 & 2 & 1 & 1 & 1 & 1 & 3 & 4 & 1 \\
1 & 1 & 1 & 1 & 1 & 7 & 2 & 3 & 7 & 10 & 1 & 1 & 5 & 1 & 1 & 3 & 1 & 10 \\
1 & 1 & 1 & 1 & 1 & 5 & 4 & 4 & 3 & 10 & 1 & 1 & 7 & 4 & 3 & 4 & 10 & 1 \\
1 & 1 & 1 & 1 & 1 & 1 & 10 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
1 & 1 & 1 & 1 & 1 & 3 & 8 & 3 & 2 & 1 & 1 & 1 & 6 & 3 & 5 & 1 & 1 & 1 \\
2 & 1 & 1 & 1 & 1 & 1 & 9 & 1 & 1 & 1 & 3 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
2 & 1 & 1 & 1 & 1 & 1 & 8 & 2 & 1 & 1 & 6 & 1 & 9 & 1 & 1 & 1 & 1 & 1
\end{array}\right] \end{array} \begin{array}{c} \\ A_1 \\ A_2 \\ A_3 \\ A_4 \\ A_5 \\ A_6 \\ A_7 \\ A_8 \\ A_9 \\ A_{10} \\ A_{11} \\ A_{12} \\ A_{13} \\ A_{14} \\ A_{15} \\ A_{16} \\ A_{17} \\ A_{18} \\ A_{19} \\ A_{20} \end{array}$$

Where,

C_1 = Low severity cracking (CL)
C_2 = Medium severity Cracking (CM)
C_3 = High severity cracking (CH)
C_4 = Low severity potholes (PL)
C_5 = Medium severity potholes (PM)
C_6 = High severity potholes (PH)
C_7 = Low severity raveling (RL)
C_8 = Medium severity raveling (RM)
C_9 = High severity raveling (RH)
C_{10} = Low severity patching (PAL)
C_{11} = Medium severity patching (PAM)
C_{12} = High severity patching (PAH)
C_{13} = Low severity rutting (RUL)
C_{14} = Medium severity rutting (RUM)
C_{15} = High severity rutting (RUH)
C_{16} = Low severity edge failure (EL)
C_{17} = Medium severity edge failure (EM)
C_{18} = High severity edge failure (EH)

In almost all the stretches, the ratings on most of the parameters were found to be low with very high ratings in a few ones. For example, in section 17 (A_{17}), all the stretches except for C_7 (Low severity raveling) are having the highest possible score of 10. However, for stretch No. 13 (A_{13}) a number of distresses are quite prominent.

Stage 4: To find the weights of the distresses, the opinions of 20 experts collected through questionnaire survey were utilized (Table 4.13). Due to the presence of uncertainty and the weights being subjective in nature, the opinions were sought in five linguistic variables such as "Negligible (N)", "low (L)", "Medium (M)", "High (H)", "Very High (H)". These linguistic variables were converted into weights and then were expressed in Triangular Fuzzy Number (TFNs). The TFNs were chosen in this study in a scale of 0 to 1 (Chen-Tung Chen, 2001). After consulting with a few experts and taking clue from literature, the weights for various linguistic variables were decided and have been presented in Table 6.4 and also represented graphically in Fig. 6.2. For example, in table and fig, TFN for Medium is (0.3, 0.5, 0.7), where 0.5 is the most possible value of a fuzzy number and 0.3 and 0.7 are the lower and upper bounds.

Table 6.4: Triangular Fuzzy Numbers (TFNs) for Linguistic Variables

Linguistic Variable	Triangular Fuzzy Number
Negligible	(0, 0, 0.1)
Low	(0, 0.1, 0.3)
Medium	(0.3, 0.5, 0.7)
High	(0.7, 0.9, 1)
Very High	(0.9, 1, 1)

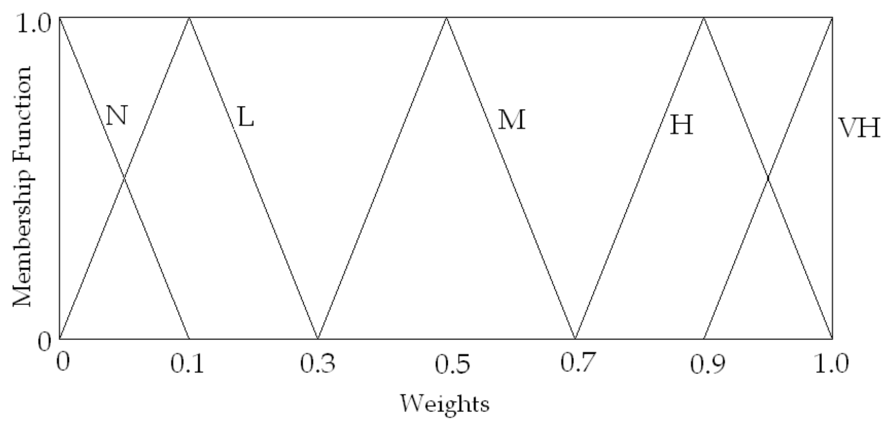


Fig. 6.2: TFNs for different Weights

Stage 5: The experts opinions obtained in the form of linguistic variables as presented in Table 4.13 are to be converted into Triangular Fuzzy Numbers (TFNs) using Table 6.4 and the responses received from the experts (E1, E2,……,E20) are presented in Table 6.5. For example, in the table an expert 1 has given weight in linguistic variable 'High' for high severity cracking and accordingly fuzzy number of (0.7, 0.9, 1.0) has been assigned in Table 6.5.

Stage 6: To normalize the differences existing in expert opinion, a simple average of fuzzy number for each distress criteria was calculated and the corresponding weights were worked out and have been presented in Table 6.6. Fuzzy weights for all criteria can be expressed in the form of the column matrix as shown in Eq. 6.4.

Table 6.5: TFNs for various distress parameters

Distress Parameter	Experts									
	E1	**E2**	**E3**	**E4**	**E5**	**E6**	**E7**	**E8**	**E9**	**E10**
(CL)	(0.0, 0.1, 0.3)	(0.0, 0.0,0.1)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)
(CM)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)
(CH)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.9, 1.0, 1.0)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)
(PL)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.0. 0.0, 0.1)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)
(PM)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.0, 0.1, 0.3)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)
(PH)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)
(RL)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)
(RM)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)
(RH)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)
(PAL)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.3, 0.5, 0.7)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)
(PAM)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.7, 0.9, 1.0)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)
(PAH)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.9, 1.0, 1.0)	(0.3, 0.5, 0.7)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)
(RUL)	(0.3, 0.5, 0.7)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)
(RUM)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.3)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)
(RUH)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)
(EL)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)
(EM)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)
(EH)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)

(Table 6.5 Continued…)

Distress Parameter	Experts									
	E11	**E12**	**E13**	**E14**	**E15**	**E16**	**E17**	**E18**	**E19**	**E20**
(CL)	(0.0, 0.1, 0.3)	(0.0, 0.0,0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0,0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0,0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0,0.1)	(0.0, 0.0,0.1)	(0.0, 0.0,0.1)
(CM)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)
(CH)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)
(PL)	(0.3, 0.5, 0.7)	(0.0, 0.1,0.3)	(0.0, 0.1,0.3)	(0.0, 0.0,0.1)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.0,0.1)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)
(PM)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)
(PH)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)
(RL)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)
(RM)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)
(RH)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.9, 1.0, 1.0)	(0.9, 1.0, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)
(PAL)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.0,0.1)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)
(PAM)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)
(PAH)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)
(RUL)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)
(RUM)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)
(RUH)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.3, 0.5, 0.7)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)
(EL)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0,0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.0, 0.1)
(EM)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.0, 0.1, 0.3)	(0.0, 0.1, 0.3)	(0.3, 0.5, 0.7)	(0.0, 0.1, 0.3)
(EH)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.0, 0.0, 0.1)	(0.0, 0.0, 0.1)	(0.3, 0.5, 0.7)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)	(0.7, 0.9, 1.0)

LEGEND: CL=Low level cracking CM=Medium level cracking CH =High level cracking PL=Low level potholes PM=Medium level pothole PH =High level potholes RL=Low level raveling RM=Medium level raveling RH=High level raveling PAL=Low level patching PAM=Medium level patching PAH=High level patching RUL=Low level rutting RUM=Medium level rutting RUH=High level rutting EL=Low level edge failure EM=Medium level edge failure EH=High level edge failure

$$\widetilde{W}_j = \begin{bmatrix} \widetilde{w}_1 \\ \widetilde{w}_2 \\ \vdots \\ \widetilde{w}_M \end{bmatrix} \qquad (6.4)$$

Where, $\widetilde{w}_1, \widetilde{w}_2 ...., \widetilde{w}_M$ are the fuzzy weights for all criteria expressed in TFNs i.e. $\widetilde{w}_j = (\widetilde{w}_{j1}, \widetilde{w}_{j2}, \widetilde{w}_{j3})$ $\forall$ j= 1, 2, 3…….M

Table 6.6: Fuzzy weights for various distress parameters

Criteria/ Distress Parameter	Fuzzy Weight
CL	(0.000, 0.045, 0.190)
CM	(0.165, 0.315, 0.510)
CH	(0.530, 0.710, 0.840)
PL	(0.195, 0.355, 0.550)
PM	(0.565, 0.760, 0.890)
PH	(0.860, 0.980, 1.000)
RL	(0.045, 0.110, 0.260)
RM	(0.195, 0.330, 0.505)
RH	(0.610, 0.785, 0.895)
PAL	(0.045, 0.110, 0.260)
PAM	(0.220, 0.380, 0.570)
PAH	(0.570, 0.755, 0.880)
RUL	(0.015, 0.075, 0.230)
RUM	(0.200, 0.360, 0.555)
RUH	(0.590, 0.775, 0.895)
EL	(0.015, 0.065, 0.210)
EM	(0.195, 0.330, 0.505)
EH	(0.590, 0.750, 0.850)

It may be observed from the table that fuzzy weight of the high severity pothole is quite high with a value (0.860, 0.980, 1.000) and that of the low severity cracking is low with a value (0.000, 0.045, 0.190). This is because of the fact that in the opinion of the experts the influence of potholes was high whereas the influence of low severity cracking was low. This was also observed in the roughness model developed in this study (Eq. 5.8), in which the coefficient of high severity pothole was quite high and that of low severity cracking was low.

Stage 7: Fuzzy prioritization value $(\tilde{p}_i)$ is then calculated by multiplying the rating matrix with the fuzzy weight matrix and summed up separately for each section, which has been presented in Table 6.7. This process is expressed mathematically as follows.

$$\tilde{P}_i = \sum_{j=1}^{M} R_{ij} \otimes \tilde{w}_j, \qquad \forall\ i=1,2,\ldots\ldots N \quad \text{and} \quad \forall\, j= 1,2,3\ldots\ldots M \qquad (6.5)$$

Where,

R_{ij} is the real number for the pavement section A_i and criteria C_j

$\tilde{w}_j$ is the fuzzy weight matrix

Table 6.7: Fuzzy prioritization values for all the stretches

Stretch	Fuzzy Prioritization value
$\tilde{p}_1$	(16.22, 23.07, 30.23)
$\tilde{p}_2$	(9.09, 14.42, 21.46)
$\tilde{p}_3$	(7.40, 11.02, 15.41)
$\tilde{p}_4$	(11.40, 16.54, 23.07)
$\tilde{p}_5$	(10.14, 15.34, 21.93)
$\tilde{p}_6$	(7.96, 12.93, 20.04)
$\tilde{p}_7$	(9.09, 13.21, 17.84)
$\tilde{p}_8$	(17.93, 26.01, 35.31)
$\tilde{p}_9$	(17.55, 25.87, 35.39)
$\tilde{p}_{10}$	(14.74, 19.85, 24.43)
$\tilde{p}_{11}$	(21.85, 29.91, 37.81)
$\tilde{p}_{12}$	(17.98, 25.01, 31.69)
$\tilde{p}_{13}$	(25.00, 35.20, 45.56)
$\tilde{p}_{14}$	(11.39, 16.19, 21.54)
$\tilde{p}_{15}$	(20.67, 27.52, 34.57)
$\tilde{p}_{16}$	(15.06, 22.04, 31.03)
$\tilde{p}_{17}$	(6.01, 8.98, 12.94)
$\tilde{p}_{18}$	(11.48, 16.36, 22.16)
$\tilde{p}_{19}$	(6.41, 9.68, 14.01)
$\tilde{p}_{20}$	(7.34, 11.64, 17.80)

Stage 8: To establish the relative preference of all the stretches, difference between all combinations of the fuzzy prioritization values has been computed, i.e fuzzy prioritization value of section 1 should be compared with all other sections and so on. This is mathematically expressed as

$$(\widetilde{F}_{ij}) = (\widetilde{p}_i - \widetilde{p}_j) \qquad \forall \text{ i= 1 to N} \qquad \forall \text{ j= 1 to N} \quad \text{and} \quad i \neq j \qquad (6.6)$$

It is to be noted that $\widetilde{p}_i$ and $\widetilde{p}_j$ are the Triangular Fuzzy Numbers, hence $(\widetilde{p}_i - \widetilde{p}_j)$ is also Triangular Fuzzy Number. Suppose $\widetilde{p}_i$ is the triangular fuzzy number (x,y,z) and $\widetilde{p}_j$ is another triangular fuzzy number (u,v,w) then the difference of $(\widetilde{p}_i - \widetilde{p}_j)$ is (x-w, y-v, z-u). A sample of these values has been presented in Table 6.8.

Table 6.8: Sample of Fuzzy Relative Preference Values

$\widetilde{p}_1 - \widetilde{p}_2$	(-5.24, 8.66, 21.15)
$\widetilde{p}_1 - \widetilde{p}_3$	(0.81, 12.05, 22.83)
$\widetilde{p}_1 - \widetilde{p}_4$	(-6.85, 6.53, 18.84)
$\widetilde{p}_1 - \widetilde{p}_5$	(-5.71, 7.73, 20.10)
$\widetilde{p}_1 - \widetilde{p}_6$	(-3.83, 10.16, 22.27)
: : :	: : :
$\widetilde{p}_{19} - \widetilde{p}_{20}$	(-6.67, 1.96, 11.39)

Stage 9: In this stage the fuzzy preference relation matrix *[E]* was developed, to know the degree of preference of stretch A_i over stretch A_j.

$$E = \begin{bmatrix} e_{11} & e_{12} & \cdots & e_{1N} \\ e_{21} & e_{22} & \cdots & e_{2N} \\ \cdots & \cdots & \cdots & \cdots \\ e_{N1} & e_{N2} & \cdots & e_{NN} \end{bmatrix} \qquad (6.7)$$

Where, e_{ij} is the real number indicating the degree of preference between the respective i^{th} and j^{th} pavement stretches. It has been calculated using positive (S_{ij}^{+}) and negatives areas (S_{ij}^{-}) of difference between two fuzzy values $(\tilde{p}_i - \tilde{p}_j)$.

$$e_{ij} = \frac{S_{ij}^{+}}{S_{ij}^{+} + \left|S_{ij}^{-}\right|} \qquad (6.8)$$

Where,

$(S_{ij}^{+} + \left|S_{ij}^{-}\right|)$ = Total area of $(\tilde{p}_i - \tilde{p}_j)$

Positive and negative areas have been computed using the membership function $[\mu_{\tilde{F}_{ij}}(x)]$ of the $(\tilde{p}_i - \tilde{p}_j)$. An example of computation of e_{ij} is shown in Fig.6.3.

For example, if the $\tilde{F}_{12} = (\tilde{p}_1 - \tilde{p}_2)$ = (-5.24, 8.66, 21.15)

Total area form the Fig 6.3 = 13.19

Positive area = 12.21 Negative area= 0.98

$e_{12} = (12.21)/13.19$ = 0.93

Here e_{ii} =0.5 and $e_{ij} + e_{ji}$ =1.0. If e_{ij} > 0.5, the stretch A_i is to be given priority over stretch A_j and vice versa.

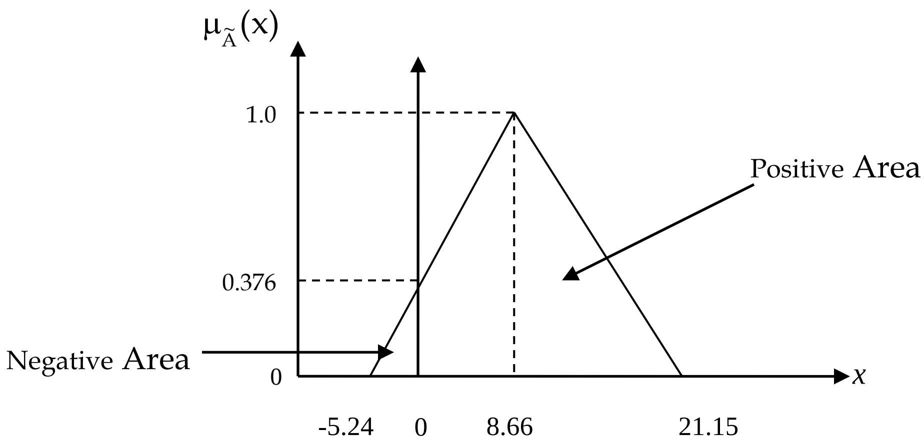


Fig. 6.3: Computation of e_{ij}

Computed values of e_{ij} for all the combinations are summarized and presented in Table 6.9.

Table 6.9: Fuzzy Preference Relation Matrix

$$\left[E_{ij}\right]_{N\times N} = \left[\begin{array}{cccccccccccccccccccc}
0.50 & 0.93 & 0.75 & 0.86 & 0.63 & 0.70 & 0.75 & 0.64 & 0.57 & 0.63 & 0.36 & 0.46 & 0.36 & 0.71 & 0.31 & 0.62 & 0.88 & 0.72 & 0.85 & 0.82 \\
0.07 & 0.50 & 0.48 & 0.63 & 0.33 & 0.42 & 0.47 & 0.35 & 0.29 & 0.32 & 0.15 & 0.21 & 0.16 & 0.41 & 0.12 & 0.33 & 0.66 & 0.44 & 0.62 & 0.57 \\
0.25 & 0.52 & 0.50 & 0.65 & 0.34 & 0.44 & 0.49 & 0.37 & 0.31 & 0.34 & 0.16 & 0.23 & 0.16 & 0.43 & 0.13 & 0.34 & 0.67 & 0.45 & 0.64 & 0.58 \\
0.14 & 0.37 & 0.35 & 0.50 & 0.22 & 0.30 & 0.34 & 0.24 & 0.19 & 0.21 & 0.08 & 0.13 & 0.09 & 0.29 & 0.06 & 0.22 & 0.52 & 0.32 & 0.49 & 0.43 \\
0.37 & 0.67 & 0.66 & 0.78 & 0.50 & 0.60 & 0.65 & 0.52 & 0.45 & 0.49 & 0.25 & 0.34 & 0.26 & 0.60 & 0.21 & 0.49 & 0.80 & 0.62 & 0.78 & 0.73 \\
0.30 & 0.58 & 0.56 & 0.70 & 0.40 & 0.50 & 0.55 & 0.43 & 0.36 & 0.40 & 0.20 & 0.28 & 0.21 & 0.49 & 0.17 & 0.40 & 0.72 & 0.52 & 0.69 & 0.64 \\
0.25 & 0.53 & 0.51 & 0.66 & 0.35 & 0.45 & 0.50 & 0.38 & 0.32 & 0.35 & 0.16 & 0.23 & 0.17 & 0.44 & 0.13 & 0.35 & 0.69 & 0.47 & 0.66 & 0.60 \\
0.36 & 0.65 & 0.63 & 0.76 & 0.48 & 0.57 & 0.62 & 0.50 & 0.43 & 0.47 & 0.25 & 0.33 & 0.25 & 0.57 & 0.21 & 0.47 & 0.78 & 0.59 & 0.75 & 0.71 \\
0.43 & 0.71 & 0.69 & 0.81 & 0.55 & 0.64 & 0.68 & 0.57 & 0.50 & 0.55 & 0.30 & 0.40 & 0.30 & 0.64 & 0.26 & 0.54 & 0.83 & 0.66 & 0.80 & 0.76 \\
0.37 & 0.68 & 0.66 & 0.79 & 0.51 & 0.60 & 0.65 & 0.53 & 0.45 & 0.50 & 0.25 & 0.34 & 0.25 & 0.60 & 0.21 & 0.50 & 0.81 & 0.62 & 0.78 & 0.73 \\
0.64 & 0.85 & 0.84 & 0.92 & 0.75 & 0.80 & 0.84 & 0.75 & 0.70 & 0.75 & 0.50 & 0.61 & 0.48 & 0.81 & 0.43 & 0.73 & 0.94 & 0.82 & 0.92 & 0.89 \\
0.54 & 0.79 & 0.77 & 0.87 & 0.66 & 0.72 & 0.77 & 0.67 & 0.60 & 0.66 & 0.39 & 0.50 & 0.38 & 0.73 & 0.33 & 0.64 & 0.89 & 0.75 & 0.87 & 0.83 \\
0.64 & 0.84 & 0.84 & 0.91 & 0.74 & 0.79 & 0.83 & 0.75 & 0.70 & 0.75 & 0.52 & 0.62 & 0.50 & 0.80 & 0.45 & 0.73 & 0.93 & 0.81 & 0.91 & 0.88 \\
0.29 & 0.59 & 0.57 & 0.71 & 0.40 & 0.51 & 0.56 & 0.43 & 0.36 & 0.40 & 0.19 & 0.27 & 0.20 & 0.50 & 0.16 & 0.40 & 0.73 & 0.53 & 0.70 & 0.65 \\
0.69 & 0.88 & 0.87 & 0.94 & 0.79 & 0.83 & 0.87 & 0.79 & 0.74 & 0.79 & 0.57 & 0.67 & 0.55 & 0.84 & 0.50 & 0.77 & 0.96 & 0.85 & 0.94 & 0.92 \\
0.38 & 0.67 & 0.66 & 0.78 & 0.51 & 0.60 & 0.65 & 0.53 & 0.46 & 0.50 & 0.27 & 0.36 & 0.27 & 0.60 & 0.23 & 0.50 & 0.80 & 0.62 & 0.77 & 0.73 \\
0.12 & 0.34 & 0.33 & 0.48 & 0.20 & 0.28 & 0.31 & 0.22 & 0.17 & 0.19 & 0.06 & 0.11 & 0.07 & 0.27 & 0.04 & 0.20 & 0.50 & 0.29 & 0.46 & 0.41 \\
0.28 & 0.56 & 0.55 & 0.68 & 0.38 & 0.48 & 0.53 & 0.41 & 0.34 & 0.38 & 0.18 & 0.25 & 0.19 & 0.47 & 0.15 & 0.38 & 0.71 & 0.50 & 0.68 & 0.63 \\
0.15 & 0.38 & 0.36 & 0.51 & 0.22 & 0.31 & 0.34 & 0.25 & 0.20 & 0.22 & 0.08 & 0.13 & 0.09 & 0.30 & 0.06 & 0.23 & 0.54 & 0.32 & 0.50 & 0.44 \\
0.18 & 0.43 & 0.42 & 0.57 & 0.27 & 0.36 & 0.40 & 0.29 & 0.24 & 0.27 & 0.11 & 0.17 & 0.12 & 0.35 & 0.08 & 0.27 & 0.59 & 0.37 & 0.56 & 0.50
\end{array}\right]$$

Stage 10: Priority Index (PI) for all the pavement stretches were computed from the fuzzy preference relation matrix using the following mathematical form (Table 6.10)

$$(PI)_i = \sum_{j=1}^{n}(e_{ij} - 0.5) \qquad \forall \ i = 1 \text{ to } N \qquad (6.9)$$

Based on the Priority Index, all twenty stretches were ranked and presented in Table 6.10. From table it may be noted that section no. 15 with priority index of 7.39 is to be given the first priority and section no. 17 with priority index of -6.89 is to be given the lowest priority.

Table 6.10: Ranking of the Pavement Stretches

Section No.	Priority Index	Rank
A_1	3.60	7
A_2	-2.97	14
A_3	-5.98	18
A_4	-1.12	10
A_5	-2.22	13
A_6	-4.18	15
A_7	-4.36	16
A_8	5.36	4
A_9	5.29	5
A_{10}	1.18	9
A_{11}	6.47	2
A_{12}	4.60	6
A_{13}	7.39	1
A_{14}	-1.66	12
A_{15}	5.68	3
A_{16}	3.26	8
A_{17}	-6.89	20
A_{18}	-1.40	11
A_{19}	-6.70	19
A_{20}	-5.36	17

The prioritization process, as explained in the above stages is quite complex and cumbersome due to a large number of stretches and criteria. Hence, a code has been developed in MATLAB [(www.mathworks.com)] and has been used in the present study. Flow chart showing all the stages in the prioritization process has been shown in Fig. 6.4.

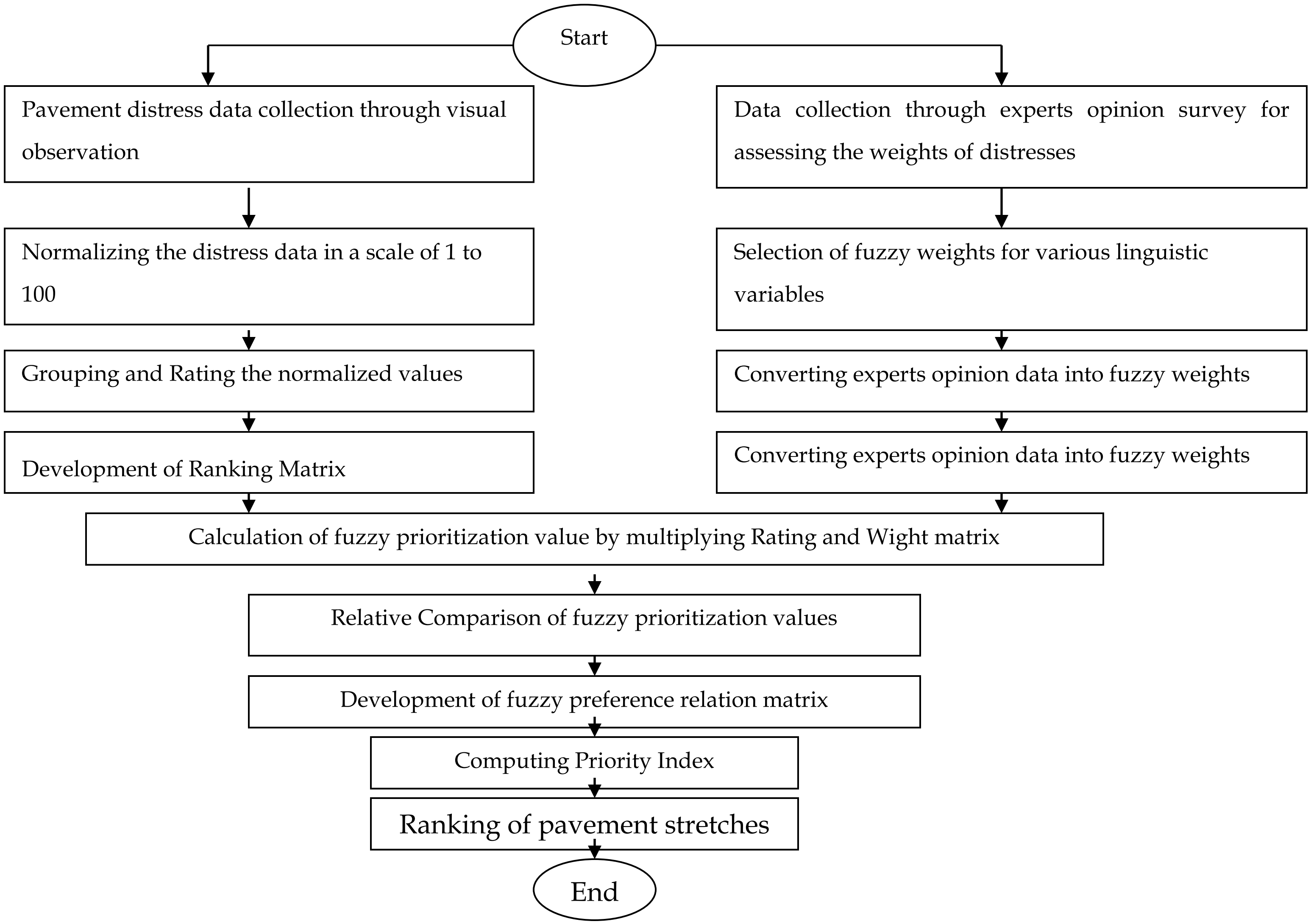


Fig 6.4: Flowchart for Prioritizing the Pavement Stretches

6.2.2.2 *Prioritization of pavement sections as per approach II*

The same stretches considered in approach -I have again been prioritized by this approach. The stages 1 to 7 discussed in approach -1 of prioritization process are the same in approach -2. In this approach, after determining the fuzzy prioritization value (Table 6.7), pavement stretches have been prioritized with the help of defuzzyfying technique. It is the process of converting the fuzzy numbers into crisp numbers. If l, m, n are the Triangular Fuzzy Numbers, corresponding crisp number is $(l + m + n) / 3$ (Chen, 1997). The fuzzy prioritization value obtained and presented in Table 6.7 for all the stretches were defuzzyfied and crisp values were calculated and they were named as Ranking Index. Based on the Index, pavement stretches were ranked (Table 6.11).

Table 6.11: Ranking of the pavement stretches

Stretch	Fuzzy prioritization value	Ranking Index	Rank
A_1	(16.22, 23.07, 30.23)	23.17	7
A_2	(9.09, 14.42, 21.46)	14.99	14
A_3	(7.40, 11.02, 15.41)	11.28	18
A_4	(11.40, 16.54, 23.07)	17.00	10
A_5	(10.14, 15.34, 21.93)	15.80	13
A_6	(7.96, 12.93, 20.04)	13.64	15
A_7	(9.09, 13.21, 17.84)	13.38	16
A_8	(17.93, 26.01, 35.31)	26.42	4
A_9	(17.55, 25.87, 35.39)	26.27	5
A_{10}	(14.74, 19.85, 24.43)	19.67	9
A_{11}	(21.85, 29.91, 37.81)	29.86	2
A_{12}	(17.98, 25.01, 31.69)	24.89	6
A_{13}	(25.00, 35.20, 45.56)	35.25	1
A_{14}	(11.39, 16.19, 21.54)	16.37	12
A_{15}	(20.67, 27.52, 34.57)	27.58	3
A_{16}	(15.06, 22.04, 31.03)	22.71	8
A_{17}	(6.01, 8.98, 12.94)	9.31	20
A_{18}	(11.48, 16.36, 22.16)	16.67	11
A_{19}	(6.41, 9.68, 14.01)	10.03	19
A_{20}	(7.34, 11.64, 17.80)	12.26	17

It may be noted from the table that stretch no. 13 ranked first with Ranking Index of 35.25 and section no. 17 was the last ranked with Ranking Index of 9.31.

6.2.2.3 Prioritization of pavement sections as per approach III

In Approach – I and approach - II of prioritization process, fuzzy weights of the various pavement distress parameters was calculated by taking the simple average of the weights obtained from 20 experts. To check the consistency in weights suggested by various experts, in the approach –III, the weights suggested by the experts were taken individually, instead of aggregating them. Pavement stretches were prioritized using the weights suggested by the individual expert (Table 6.5) for various distress parameters. The rankings were obtained using the same steps as followed in approach –I and 20 such rankings obtained from 20 experts have been presented in Table 6.12. Finally, the ranks thus obtained were summed up and the pavement stretches were ranked based on the aggregated value as shown in Table 6.13.

Table 6.12: Ranking of Pavement as per the Opinion given by Individual Expert

Stretch No	Ranking Based on Individual Expert Opinion																			
	E1	E2	E3	E4	E5	E6	E7	E8	E9	E10	E11	E12	E13	E14	E15	E16	E17	E18	E19	E20
A_1	7	8	5	8	9	7	9	5	8	6	9	7	7	6	6	6	8	6	8	5
A_2	14	14	12	15	14	10	15	13	10	10	15	16	11	14	13	14	16	16	15	15
A_3	18	18	18	17	18	17	17	17	17	17	18	18	18	18	16	18	17	18	18	18
A_4	13	11	15	11	8	13	14	15	9	12	8	10	13	10	9	11	15	10	9	10
A_5	9	13	14	14	12	14	13	14	13	14	12	14	10	11	12	13	14	14	12	14
A_6	15	15	17	12	17	18	16	18	16	18	13	12	17	15	17	15	13	11	14	12
A_7	17	16	13	16	16	15	12	12	18	15	16	15	16	16	18	16	12	15	16	16
A_8	3	2	7	5	3	5	5	8	4	5	3	4	5	2	3	4	5	5	4	6
A_9	2	3	6	7	4	3	4	7	7	4	4	5	3	5	4	2	4	7	5	7
A_{10}	11	9	9	9	11	9	7	9	12	9	11	8	9	9	10	8	6	8	10	8
A_{11}	4	4	4	2	6	2	2	2	2	2	2	3	4	8	1	1	1	3	2	2
A_{12}	8	7	3	6	7	4	8	4	6	3	7	6	6	4	5	5	7	4	7	4
A_{13}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	3	2	1	1	1
A_{14}	12	10	10	10	13	12	10	10	14	13	14	13	14	13	14	12	10	13	13	13
A_{15}	6	5	2	3	2	6	3	3	3	7	5	2	2	3	7	7	3	2	3	3
A_{16}	5	6	8	4	5	8	6	6	5	8	6	9	8	7	8	9	9	9	6	9
A_{17}	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
A_{18}	10	12	11	13	10	11	11	11	11	11	10	11	12	12	11	10	11	12	11	11
A_{19}	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19
A_{20}	16	17	16	18	15	16	18	16	15	16	17	17	15	17	15	17	18	17	17	17

Table 6.13: Ranking of Pavement Stretches

Stretch No.	Experts Ranks aggregated value	Rank
A_1	140	7
A_2	272	14
A_3	351	18
A_4	226	11
A_5	256	13
A_6	301	15
A_7	306	16
A_8	88	4
A_9	93	5
A_{10}	182	9
A_{11}	57	2
A_{12}	111	6
A_{13}	24	1
A_{14}	243	12
A_{15}	77	3
A_{16}	141	8
A_{17}	400	20
A_{18}	222	10
A_{19}	380	19
A_{20}	330	17

The stretch No. 13 got the highest rank with a lowest aggregate value of 24 and stretch No. 17 the last rank with highest value of 400 (Table 6.13)

6.2.3 Comparison of the Approaches

Ranks obtained from the Approaches I, II and III were compared as shown in Fig. 6.5. It may be observed that the ranking pattern obtained by three approaches is almost similar with slight variation in two cases. In approach-III stretch number four got 11th rank and eighteen got 10th rank, whereas in approach-I and II they were just the reverse. This indicates that the ratings suggested by the experts were consistent and there was no wide variation in their perception.

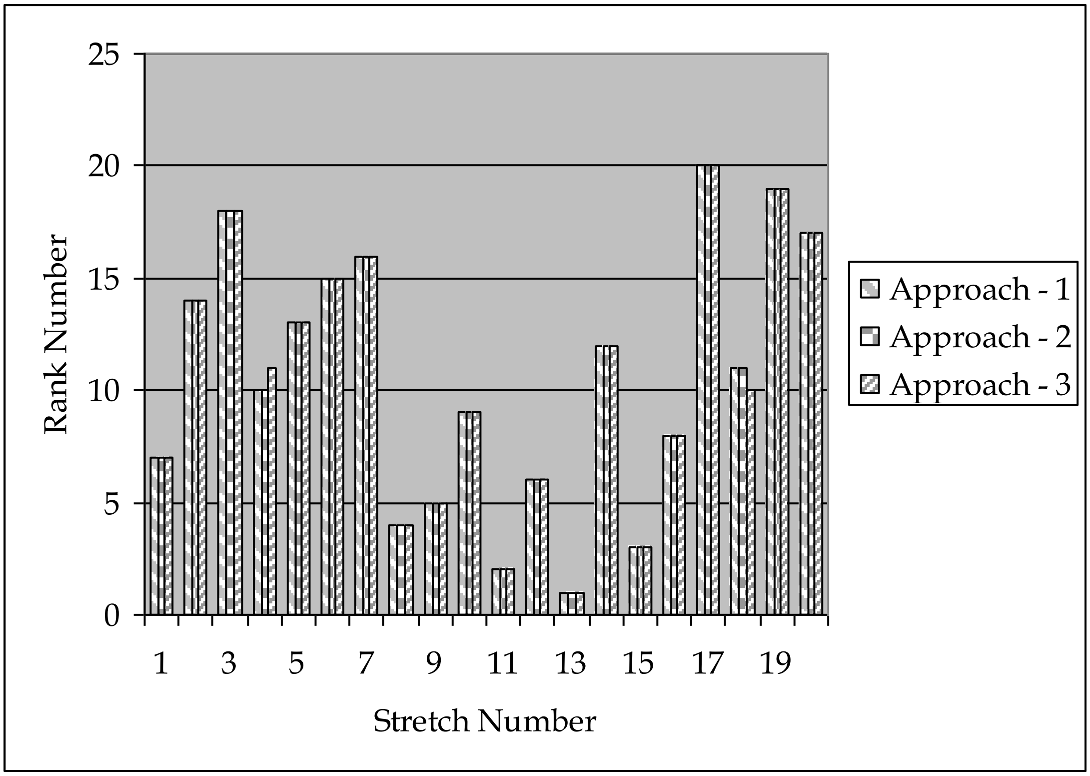


Fig 6.5: Comparison of Ranks as per Approaches I, II and III

Though the ranking patterns obtained by all the three approaches are similar, at present it was decided to use the Approach – II for ranking the pavement stretches due to its simplicity.

6.2.4 Ranking of Pavement Stretches in Network of Roads

In case of network level maintenance, the stretches would be from different functional class of highway. Hence, high preference should be given to the highways based on their importance and traffic. Accordingly, the ranking index obtained in approach – II (Table 6.11) would be multiplied with the prioritization factor as presented in Table 6.14. This prioritization factor is based on the functional class of the highway, which is again classified into three levels and number of the commercial vehicles passes per day (Reddy and Veeraragavan, 2002). Based on the new Ranking Index obtained after multiplying with prioritization factor, ranking is to be done. For easy identification of the stretch from different functional class of highway a code number is given and has also been presented in Table 6.14.

Table 6.14: Prioritization Factor for Different Functional Class of Highways and Traffic

Functional Class	**Level**	**No. of Commercial Vehicles**	**Prioritization Factor (F)**	**Code**
Express way/ National Highway	High	>5000	1	1
	Medium	3000-5000	0.9	2
	Low	<3000	0.8	3
State Highway	High	>3000	0.8	4
	Medium	1500-3000	0.75	5
	Low	<1500	0.7	6
Other Roads	High	>1500	0.75	7
	Medium	500-1500	0.7	8
	Low	<500	0.6	9

6.3 GROUPING OF THE PAVEMENT STRETCHES USING CLUSTERING TECHNIQUE

When large number of pavement stretches are to be maintained, it is practically difficult to carryout individual rank wise maintenance program as number of stretches may have similar distresses with minor variations. In such situations grouping or clustering the pavement stretches would be the best option. Hence in the present study an attempt was made to group the pavement stretches according to pavement condition using the clustering technique. This helps to identify and prioritize a group of pavement stretches so that maintenance measures could be taken accordingly.

As discussed in the literature, number of clustering techniques are available for groping of data points, among them K-means clustering technique has been chosen in the present study, because of its simplicity in usage, accuracy and efficiency.

6.3.1 The K-Means Algorithm

K-Means is one of the simplest partitional algorithms that solve most of the well known clustering problem (Hamerly, 2003). The objective of the K-means is to find the partition of the data, which minimize the squared-error or the sum of the squared distances between all the points and their respective cluster centers. In other words, K-Means minimize the intra cluster distance. The algorithm is composed of the following steps (Jain et al., 1999; Turi, 2001)

- *i.* Choose K initial cluster centers.
- ii. Assign each data point to the group that has the closest center by calculating the distance between all the centers and the data points.
- *iii.* After assigning all the data points, recalculate the positions of the K centers.
- iv. Repeat second and third steps until the K centers will no longer move.

6.3.2 Grouping Process

To explain the grouping process an example with 20 pavements sections data presented in Table 4.4 in chapter 4 has been considered.

6.3.2.1 Grouping Stages

Phase-I: Pavement distresses have different weightages, hence all the distresses were multiplied with corresponding fuzzy weights and the fuzzy prioritization values were found for all the stretches. Process of calculating the fuzzy prioritization value has been discussed in section 6.2.2.1 . The first seven stages (1 to 7) are being used for this purpose and fuzzy prioritization values are presented in the Table 6.7 are taken as an example.

Phase II: Fuzzy prioritization values for all the stretches were grouped with the help of K-means clustering technique as discussed in 6.3.1. A suitable code has been developed in MATLAB and used for clustering the pavement stretches. Flowchart for K-Means clustering technique has been shown in Fig. 6.6.

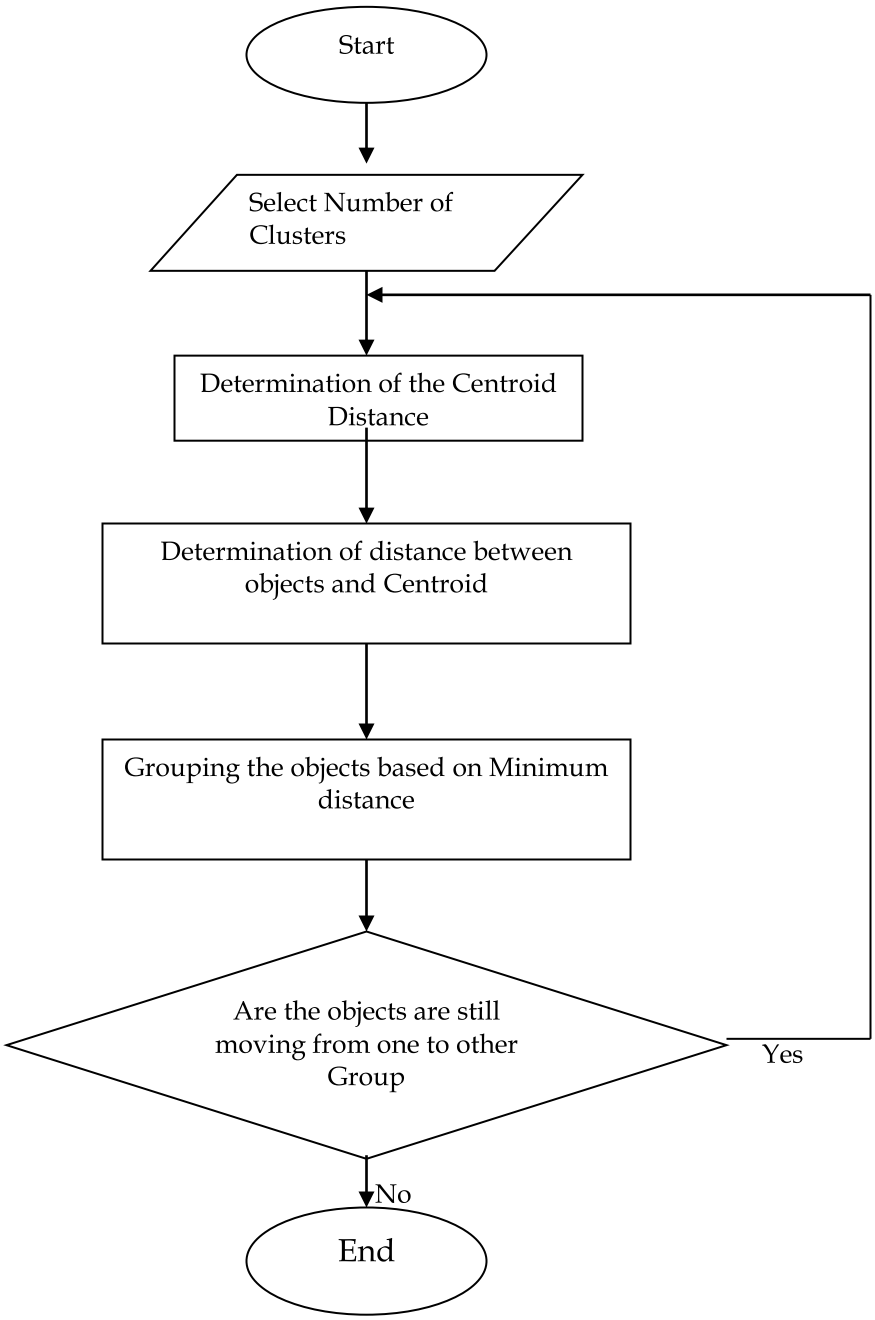


Fig 6.6: Flow Chart for K-Means Clustering Technique

6.3.2.2 Finding the Optimum Number of Clusters (ONC)

As discussed in K-means clustering technique algorithm it is necessary to give the number of the groups to be made as a input. Hence, it would be very difficult to specify the optimum number of clusters/groups. Since it is not possible to fix the number of clusters for any given data set, in the present study, an iterative algorithm has been developed to find the number of clusters, as detailed below.

Step 1: Using the code developed in MATLAB for K-Means clustering technique, the fuzzy evaluation values were clustered into homogeneous groups.

Step 2: Cluster centroid was calculated using the Equation 6.10

$$\overline{x_j} = \sum_{i=1}^{n} x_{ij} / n \quad \forall \; j = 1, \ldots, 5 \tag{6.10}$$

Where, j is the number of variables in one data point

n is the number of data points in a cluster

$\overline{x_j}$ is the j^{th} column centroid

x_{ij} is the data point in i^{th} row and j^{th} column

$\forall$ represents for all

Step 3: For all the individual clusters in a cluster group, the distance between data points and its cluster centroid (also known as intra cluster distance) was computed using Equation 6.11

$$D_i = \sqrt{\sum_{i=1}^{n} (x_{ij} - \bar{x}_j)^2} \quad \forall \; i = 1, \ldots, n \text{ and } \forall \; j = 1, \ldots, 5 \tag{6.11}$$

Where D_i is the distance of i^{th} row in a cluster from its centroid & remaining parameters are as explained in Equation 6.10

Step 4: The Average of all the distances from each data point and its corresponding cluster centroid was computed for all the individual clusters in a chosen cluster group using Eq. 6.12. Further, the weighted averages of the distances of the each cluster group were calculated using Equation 6.13. The outcome of this exercise is presented in Table 6.15.

$$\overline{D}_k = \frac{1}{n}\sum_{i=1}^{n} D_i \quad \forall\ k = 1,\ldots, K \text{ and } \forall\ n = 1,\ldots, K \tag{6.12}$$

Where K is the total number of clusters in a cluster group

'k' is the individual cluster number in a cluster group

'n' is the total number of data points in individual cluster

$$K_{WA} = \frac{\sum_{k=1}^{K} \overline{D}_k * n_k}{\sum_{k=1}^{K} n_k} \tag{6.13}$$

Where K_{WA} is the weighted average distance of the cluster group

Step 5: A graph was plotted between weighted average distances of all the cluster groups and the number of cluster groups as presented in Fig. 6.7. It has been observed that the weighted average distance decreases as the number of the clusters increases.

The optimum number of clusters is observed to be the point where the increase in the number of clusters does not result in any appreciable reduction in the distances. It may be observed from Fig. 6.7 that the distance of cluster groups rapidly decrease up to number five and then the gradient of the curve become comparatively flat and there is not much change in the value from 6 to 7 and further. Thus ONC in this case found to be six. As it is little difficult to understand the calculation of weighted average distance of cluster group, hence, an example has been given in *Appendix 5*.

Table 6.15: Distances and Weighted Average Distances of different Cluster Group

Number of cluster groups	Number of data points in each cluster (Average of distances of the data points form their respective cluster centers)							
	1	2	3	4	5	6	7	Weighted Average distance of cluster group
1	20 (12.15)							12.15
2	8 (5.36)	12 (4.67)						4.946
3	3 (5.12)	6 (3.85)	11 (4.21)					4.238
4	7 (3.71)	1 (0.00)	5 (2.39)	7 (2.40)				2.736
5	3 (1.70)	4 (2.57)	5 (2.39)	7 (2.40)	1 (0.00)			2.2
6	3 (1.70)	1 (0.00)	4 (2.00)	4 (2.57)	7 (2.27)	1 (0.00)		1.96
7	2 (0.87)	1 (0.00)	4 (2.00)	7 (2.27)	4 (2.04)	1 (0.00)	1 (0.00)	1.8

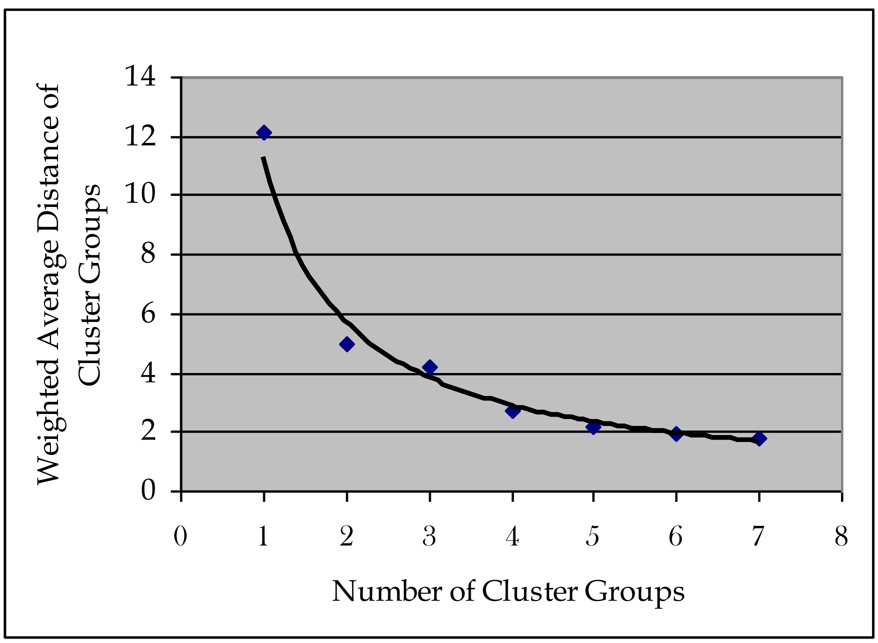


Fig 6.7: Plot between Number of Cluster Group and Weighted Average Distance of Cluster Group

6.4 CLUSTER VALIDITY TECHNIQUES

Though an algorithm has been developed and presented for finding the Optimum Number of Clusters (ONC), it was decided to cross check its acceptability through the existing cluster validity techniques. Popular techniques *viz.* Dunn's and Davies-Bouldin Indices, as detailed in the following paragraphs, have been chosen for validation.

6.4.1 Dunn's Validity Index

This technique (Dunn, 1974; Mahamed, 2004) is based on the idea of identifying the cluster sets that are compact and well separated. The main goal of Dunn's validity index is to maximize the inter-cluster distances (i.e separation) while minimizing intra-cluster distances (i.e. increase compactness). The Dunn's validation index (*DV)*, can be computed using Equation 6.14. The number of clusters, which maximizes the *DV* is considered as the ONC.

$$DV = \min_{k=1,\ldots,K}\left\{\min_{l=k+1,\ldots,K}\left\{\frac{d(c_k, c_l)}{\max_{a=1,\ldots,K}\{d'(c_a)\}}\right\}\right\} \tag{6.14}$$

Where

$d(c_k, c_l)$ is the distance between clusters c_k and c_l in the cluster group

$d'(c_a)$ is diameter of the clusters in the cluster group 'a'

K is the number of clusters in a group.

6.4.2 Davies-Bouldin Validity Index

This index (Davies and Bouldin, 1979; Mahamed, 2004) is a function of the ratio of the sum of intra-cluster scatter to inter-cluster separation. The ratio is small if the clusters are compact and far from each other. Consequently, Davies-Bouldin index (DB) will have a small value for ONC. The DB index can be computed using Equation 6.15.

$$DB = \frac{1}{K}\sum_{k=1}^{K}\max_{\substack{l=1,\ldots,K \\ k\neq l}}\left(\frac{d^{'}(c_k)+d^{'}(c_l)}{d(c_k,c_l)}\right) \tag{6.15}$$

All the parameters are as explained in Equation 6.14.

Using Equations 6.14 & 6.15, DV and DB values have been calculated for different number of clusters and presented in Table 6.16.

Table 6.16: Dunn's and DB validity indices

No. of clusters	Dunn's Index	DB Index
2	1.70	0.93
3	0.94	1.33
4	1.69	0.72
5	1.32	0.65
6	2.29	0.49
7	1.94	0.56

From the table, it can be observed very clearly the Dunn's Index gives maximum value at six numbers of clusters while the DB index, which works based on minimization criteria, also provides the ONC as six. It can be recalled here that the ONC obtained from the algorithm used in the present study was also six. Hence, it was decided that the optimum number of clusters for the data considered is 'six' and the technique proposed to find the ONC is acceptable.

6.5 SUMMARY

Weights of various distresses play an important role in prioritizing the pavement stretches. Fuzzy approach is very much suitable for assessing the weights when uncertainty is involved. Three different approaches proposed here were yielding the same results; hence any one of these methods can be used for prioritizing the pavement stretches. Process of grouping could be helpful in maintaining large number of stretches simultaneously.

CHAPTER 7

DEVELOPMENT OF SOFTWARE FOR PAVEMENT MAINTENANCE AT NETWORK LEVEL

7.1 BACKGROUND

The details of methodology, data collection and analysis for developing a PMMS have already been discussed in the previous chapters. Development of the user friendly software and its application has been discussed in the current chapter. This would assist the organizations or Public Works Department (PWD) engineers while taking the decisions for distributing available funds in an optimal and logical manner for maintaining the network of roads. As roughness is the main indicator of functional condition of the pavement, this software would predict the change in roughness based on the kind of maintenance work taken up.

Keeping in view the fact that the networks could be small or large, two softwares were developed with slight modifications, one for maintaining the pavement as per individual rank wise and other one for group wise. The procedure followed for prioritizing pavements individually or group wise ranking as presented in articles 6.2 and 6.3 was integrated in the software package. Pavement roughness model developed and presented in Eq. 5.8 also was also integrated for predicting roughness from the observed distress parameters.

In addition, options were provided for selecting the type of maintenance activity based on the availability of funds. If enough fund is available provisions could be made for overlay, otherwise the pavement condition could be improved by repairing the distress parameters. Accordingly, software would calculate the requirement of funds for selected maintenance work and predict the roughness of stretches after carrying out repair works. An easily understandable output file in Microsoft Excel format would then be generated, which would show the summary of various maintenance operations suggested for different stretches, final roughness after the maintenance and total money spent for maintenance.

7.2 DEVELOPMENT AND OPERATION OF SOFTWARE PACKAGE

An user friendly software package was developed in visual basic environment for maintenance of the flexible pavements. Visual basic is an ideal programming language for developing sophisticated professional applications which makes use of Graphical User Interface for creating robust and powerful applications (Perry, 1998). Various stages in software operations have been discussed in the following sections.

7.2.1 Entering the Details of the Roads

The details regarding the name of the roads, functional classification, width of the carriage way, length of the stretches and chainage are to be provided at this stage. In addition, Microsoft Excel file is to be created and its path need to be given to store the output data. Sample screen for entering the various details of pavement is shown in Fig 7.1. Help button is also provided to guide the users to fill in the data and it could be referred to in case of any difficulty while entering the data. This software is designed to cater for both small and large network of roads. After furnishing all the details, software would ask for the pavement condition data against each stretch.

7.2.2 Entering the Pavement Condition Data

Pavement distresses such as cracking, potholes, patching, raveling, rutting and edge failure data in three severity levels namely low, medium and high collected over each stretch have to be given as inputs. All the distress parameters except rutting are to be entered in percentage of total area and rutting needs to be entered in length per km. In case of network level maintenance where the stretches are from different functional classes of highway, the code number is to be entered for all the stretches as per Table 6.14. This code is based on the functional class of highway and traffic levels and it indicates the level of importance a stretch.

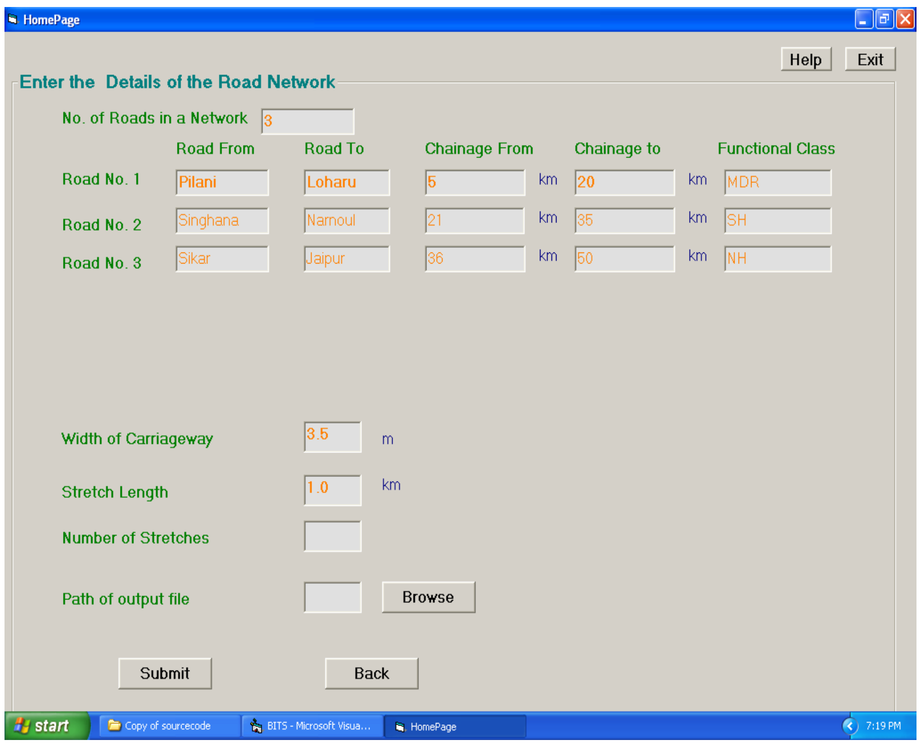


Fig 7.1: Sample Screen for Entering the Details of Pavement Stretch

Pavement condition data could be entered in two ways. Data may be put in a file Microsoft Excel sheet and then loaded into the system or entered through keyboard. Provision for changing the input values at any time has also been provided in the programme. Sample screen for entering pavement condition data thorough Microsoft Excel file and key board has been shown in Figs 7.2 and 7.3 respectively. In this software number of criteria or distresses has been fixed as 18 (6 distress parameters with three severity levels). However, provision has been made to increase the number depending on the need. User can save the input data by clicking the save data option at any time and can retrieve the same whenever required.

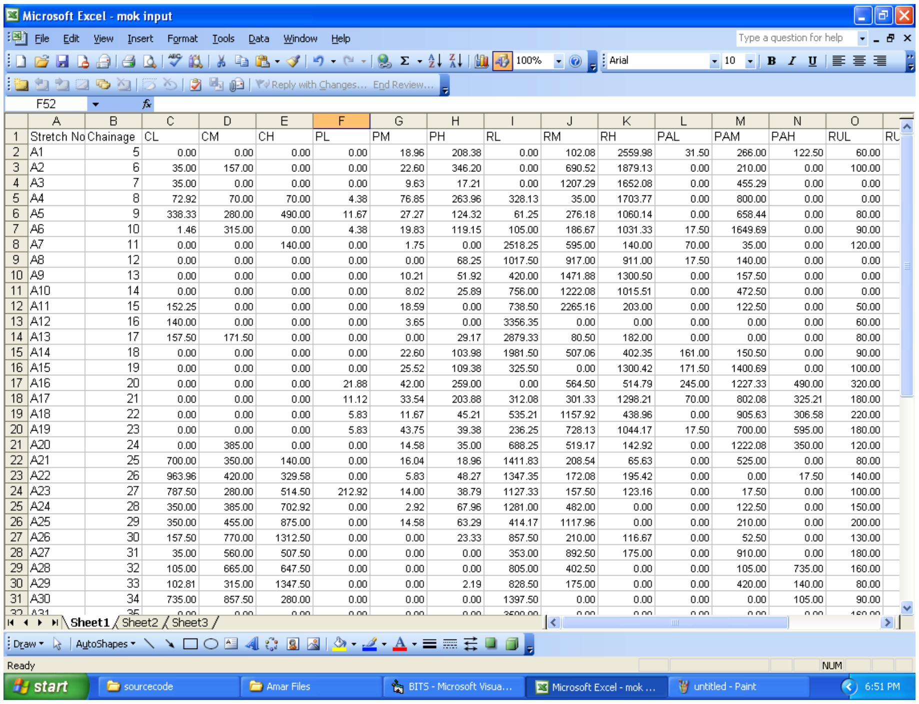


Fig 7.2 Sample Screen for Inputting Pavement Distress Data through an Excel File

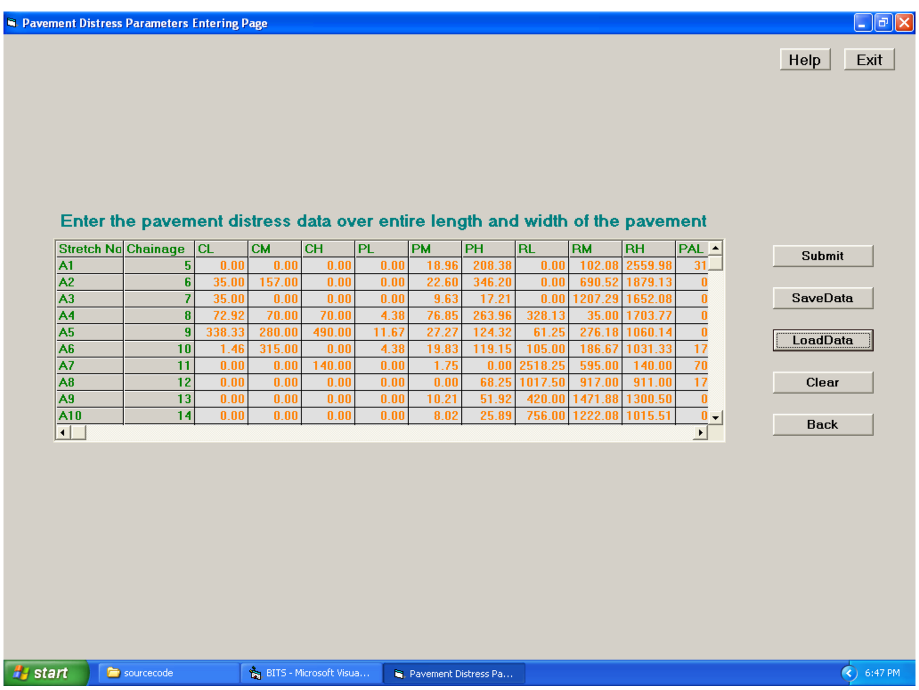


Fig.7.3: Sample Screen for Entering Pavement Distress Data through Key Board

7.2.3 Finding Ranking Index, Rank and Roughness

Based on the pavement distresses data, software would find the ranking index, rank and roughness. The procedure presented in section 6.2.2.2 would be followed for finding the Ranking Index. In case of network of roads of varying importance, the ranking index would be multiplied with the prioritization factor as detailed in section 6.2.4 and then the individual pavement stretches would be ranked. The weights of the pavement distress parameters found through the experts opinion surveys (Table 6.6) were given as default values in the software while calculating the Ranking Index. It may be noted here that users have flexibility to change the weights if they wish by conducting an expert opinion survey or by any other method of their choice.

The roughness model presented in Eq.5.8 was included in the software for predicting the total roughness, which is the sum of the roughness obtained due to the distresses and the initial roughness. It might be noted that software takes the initial roughness values of 2.4, 2.8 and 3.0 m/km for the stretches in NHs, SHs and MDRs respectively, which has been detailed in section 5.4.2. It is to be noted here that while calculating the roughness, edge failure distress parameter has not been taken into account as this would not affect the roughness. The sample screen showing the ranking index, rank and the roughness has been presented in Fig 7.4.

7.2.4 Grouping the Pavement Stretches

If the number of the stretches is not too many, the user may directly take maintenance decisions as per individual ranking of the stretches, otherwise group wise ranking would be done. The screen provided in the Fig 7.4 has also the option for grouping the pavement stretches. Using that option user can group the pavement stretches in an optimum number. The procedure detailed in the section 6.3.2 has been followed for clustering and finding the optimum number of clusters. Sample screen of displaying optimum number of the groups or clusters is shown in Fig 7.5.

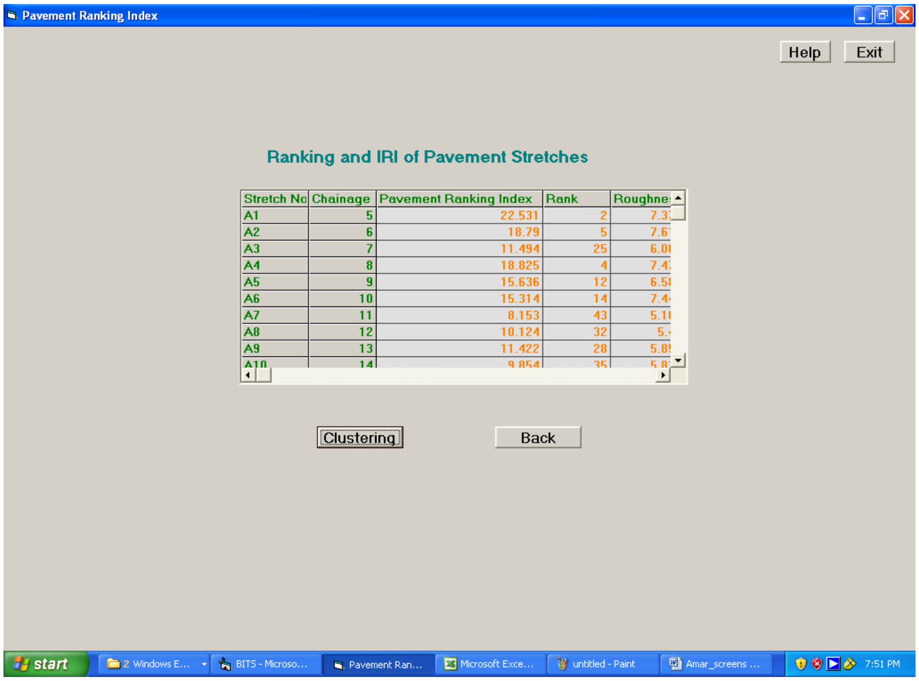


Fig 7.4: Sample Screen for Calculating the Ranking Index and the Roughness

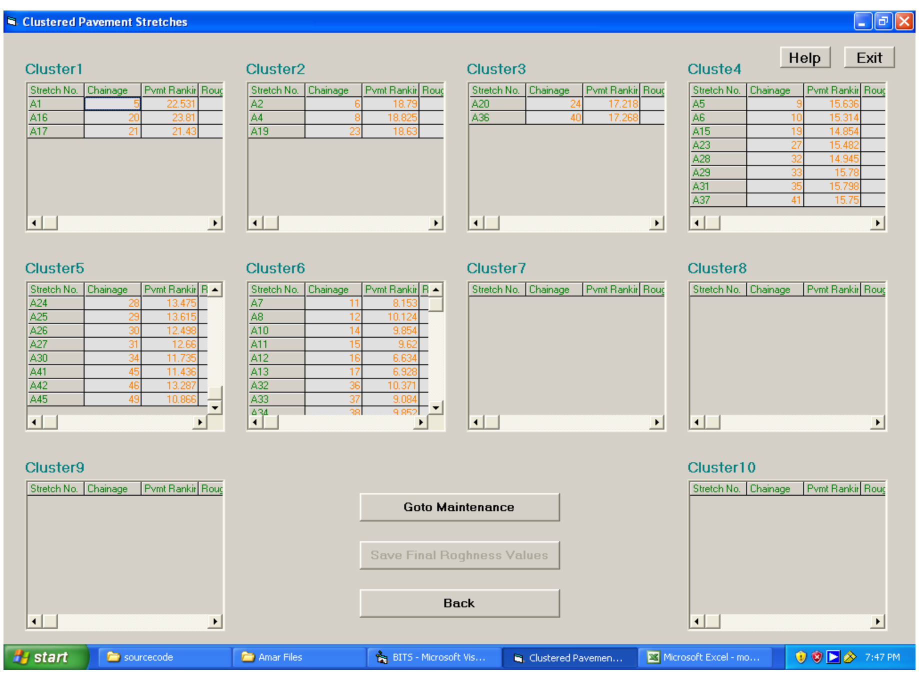


Fig 7.5: Sample Screen for Displaying Optimum Number of Groups

7.2.5 Maintenance Operations

After the prioritization of pavements, the next step is to go for the maintenance management decision. The user needs to enter the available budget and select the type of maintenance operation. There are two options, overlay or repairing of the pavement distresses. Sample screen provided in Fig 7.6 shows the options for entering of budget and selection of maintenance options.

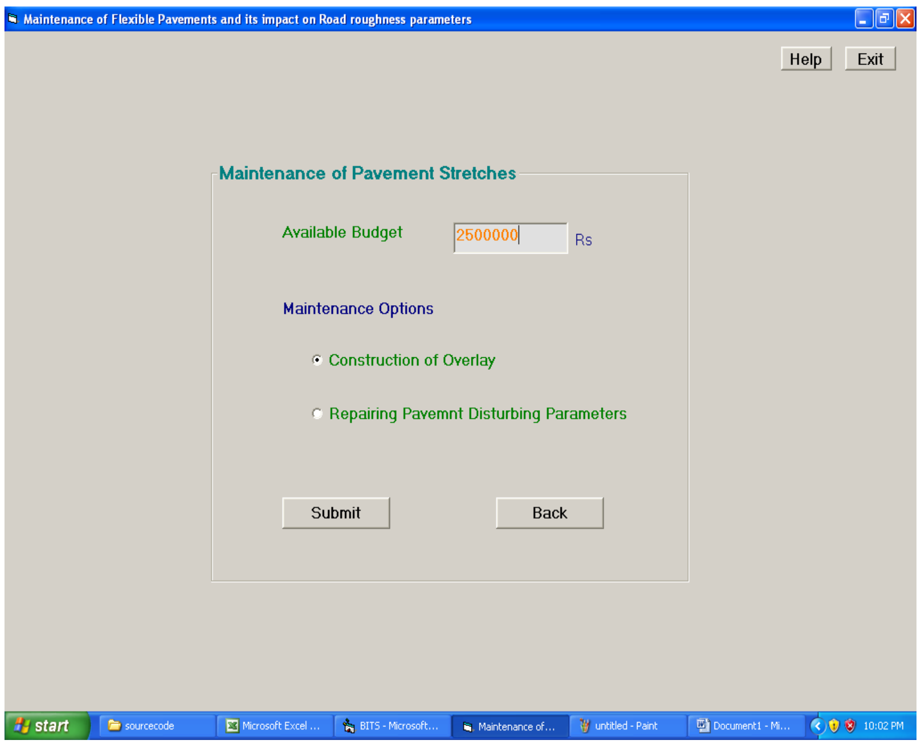


Fig 7.6: Sample Screen for Entering the Budget and Selecting the Maintenance Options

A number of researches and organizations (Reddy and Veeraragavan, 2002; Aggarwal et al., 2004; Singh and Sreenivasulu, 2005) have suggested different types of overlays and their thicknesses based on the pavement structural condition or roughness level. This study mainly concentrates in the direction of selecting the various treatments for repairing the distresses, their cost and their impact on the roughness rather than overlay design. However, when the

International Roughness Index is more than 5.5 m/km for NHs, 6.5 m/km for SHs and 7.5 m/km for MDRs, software will suggest the user to go for overlay design. Provision has been made to include the cost based on the thickness of overlay as shown in Fig. 7.7. The thickness is usually determined by conducting Benkelman Beam Deflection (BBD) survey or Falling Weight Deflectometer (FWD), which has not been included in this study. However, a separate module is to be incorporated in the software for complete overlay design.

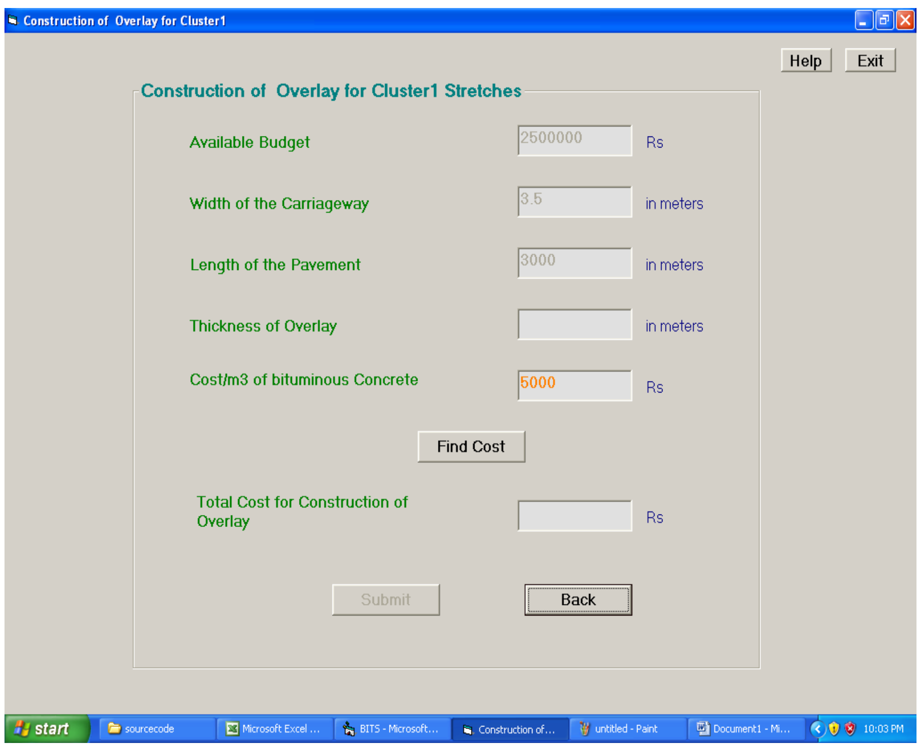


Fig 7.7: Sample Screen Showing the Information Required for Construction of Overlay

A sample screen provided in Fig 7.8 shows different types of distresses along with severities. Accordingly, user needs to select the distress to be repaired and enter the cost required for repairing the particular distress parameter. Different types of treatments are available for repairing the pavement distresses. In the present study the treatments suggested in the Guidelines for

Maintenance of Flexible Pavements (IRC: 82-1982) were chosen, which are presented in the Table 7.1.

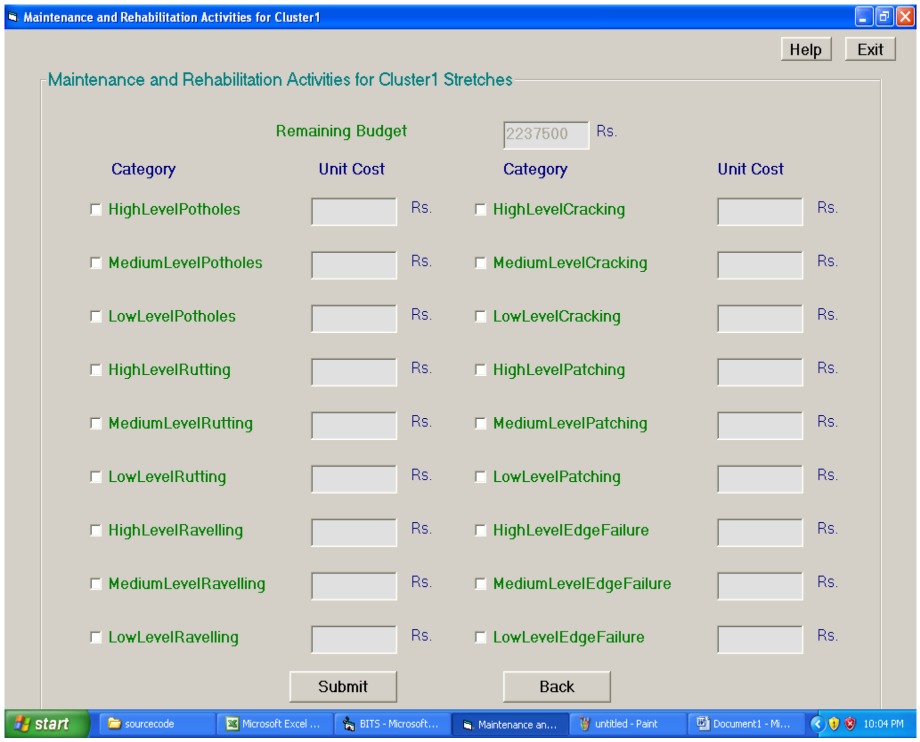


Fig 7.8: Sample Screen for Selecting Pavement Distresses for Repairing and Unit Cost for the Same

However, in most of the cases, a particular type of treatment is primarily used in a locality. For example, after discussion with the Engineers of the PWD, it was found that for medium range cracking, only fog seal was used even though there are provisions for two more possible treatments. The default value has been chosen accordingly in the software. However, there is provision for using the other treatments as well. Further, the unit cost (transportation, material and labour cost) for selected treatments have also been incorporated as presented in Table 7.2. Unit cost was obtained from the Basic Schedule of Rates (BSR) provided by public works department, Jhunjhunu District, Rajasthan. Such rates are available for different districts separately.

After selecting the type of distress for repair and entering their unit cost, the software calculates the cost and compares with the available funds. If the budget is not adequate, it will give an error message. In case of group wise maintenance, the selected distresses for repair would be considered for all the stretches within the group. Once decision regarding the maintenance of the first group is taken, software would read the remaining distresses present on the pavement stretches and based on which roughness values would be predicted using the equations developed in this study. The prioritization of the stretches would be done again considering all the stretches in the study once and again the maintenance decision would be taken. This process will be continued until the budget is exhausted.

Table 7.1: Treatments for Different Types of Distresses

S.No	Type of distress	Severity Level	Treatment
1	Cracking	Low	Spraying Bitumen binder having low viscosity
		Medium	Bitumen binder /Slurry seal / Fog seal
		High	Slurry seal/Sand bituminous premix patching
2	Raveling	Low	More quantity of binder/ fog seal
		Medium	Cutback bitumen covered with coarse sand / slurry seal
		High	Renewal coat with Premix Carpet / slurry seal
3	Potholes	Low	Premix open graded / Dense graded patching /Penetration macadam patching
		Medium	Premix open graded/ Dense graded patching/ Macadam patching
		High	Premix Open Graded or dense graded patching / Macadam patching

S.No	Type of distress	Severity Level	Treatment
4	Rutting	Low	Sand bituminous premix patching/ mixture of aggregate powder passing through 2.36 mm sieve
		Medium	Slurry seal
		High	Premix open graded or Dense graded patching along the rutted path
5	Patching	Low	Remove the damaged patch area completely and apply sand bituminous premix patching or slurry seal along the rutted path
		Medium	Remove the patch area completely and apply require depth with Premix open graded or Dense graded patching along the rutted path
		High	Remove the patch area completely and apply require depth with Premix open graded or Dense graded patching along the rutted path
6	Edge failure	Low	Spraying of bitumen/ for seal
		Medium	Repair with the same pavement material
		High	Repair with the same pavement material

Table 7.2: Unit Costs for different Treatments as Per Basic Schedule of Rates (BSR)

S.No	Type of Failure	Severity	Treatment Selected	Unit	Cost Rs.
1	Cracking	Low	Spraying Bitumen Binder	Sq.m	6.5
		Medium	Fog Seal	Sq.m	9
		High	Sand Bituminous Premix Patching	Sq.m	12
2	Raveling	Low	Fog Seal	Sq.m	9
		Medium	Sand Bituminous Premix Patching	Sq.m	12
		High	Slurry Seal	Sq.m	18
3	Potholes	Low	Premix Dense Graded Patching of 20 mm thick with seal coat	Sq.m	85
		Medium	Premix Dense Graded Patching of 50 mm thick with seal coat	Sq.m	145
		High	Penetration Macadam of 75 mm thick with	Sq.m	205

			seal coat		
4	Rutting	Low	Sand Bituminous Premix Patching	Sq.m	12
		Medium	Slurry Seal	Sq.m	18
		High	Premix Dense Graded Patching of 20 mm thick with seal coat	Sq.m	85
5	Patching	Low	Slurry Seal	Sq.m	18
		Medium	Premix Dense Graded Patching of 20 mm thick with seal coat	Sq.m	85
		High	Premix Dense Graded Patching of 50 mm thick with seal coat	Sq.m	145
6	Edge failure	Low	Fog Seal	Sq.m	9
		Medium	Premix Dense Graded Patching of 20 mm thick with seal coat	Sq.m	85
		High	Penetration Macadam with seal coat	Sq.m	205

7.3 DEMONSTRATION OF THE SOFTWARE WITH AN EXAMPLE

As an example, a total of 45 stretches comprising 15 each from three functional classes of highways such as Major District Roads, State Highways and National Highways were selected. To demonstrate the proposed software, a pavement stretch of length 1.5 km on a single lane was selected for each category of highway. This stretch was further divided into 15 uniform sections of 100 m length each. Pavement distress parameters such as cracking, raveling, potholes, patching, rutting and edge failure data in three severity levels were collected on all these sections. Data collected on a 100 m stretch was expressed in terms of 1 km by multiplying with a suitable factor. Along with the pavement condition, traffic census data was also collected from the nearest Toll Booths of each road. All these data was fed into the software as discussed in section 7.2.2. Along with this condition data, code numbers were also given as input for all the stretches based on the functional class and traffic as discussed in the section 6.2.4. Pavement distress data collected on all the 45 sections of different highways has been presented in

Table 7.3. Stretches selected from Major District Road are numbered as M-1 to M-15, from State Highway S-1 to S-15 and from National Highway N-1 to N-15. It may be observed from the table, on selected stretches high severity rutting was observed only in the NHs and the distresses such as cracking and potholes were almost absent on them. On MDR and SH most of the distresses were observed on a number of stretches, but high severity rutting was completely absent. The pavement distress data for all the stretches was fed to obtain ranking index, rank, roughness values as presented in the Table 7.3. It might be observed from the table that stretch no. S-1 with a ranking index of 23.73 was ranked first, stretch no. M-1 was ranked second with a ranking index of 22.53 and stretch no. M-12 was ranked last with an index of 6.63. A close observation of the distress data collected on different stretches reveals that, the extent and severity of distresses on a number of stretches on NHs were low when compared with those of in MDRs and SHs. However, NHs received higher preferences due to their functional importance and traffic volume.

Separate software was developed for individual rank wise and group-wise ranking of stretches for maintenance. Group wise maintenance of stretches would be discussed here. Using the grouping option as discussed in section 7.2.4, stretches were grouped into optimum number of groups. Pavement stretches considered in the present study were grouped into 5 groups as shown in Fig 7.9. It might be noted here that, though the stretches in a group are from different functional classes, their Ranking Index (RI) is not varying much. Also the groups are being ranked and logically the maintenance of the stretches in the first ranked group is to be taken up first.

Table 7.3: Pavement Distress Data Collected on Various Stretches Comprising Different Functional Classes of Highway and their Roughness, Ranking Index and Rank

Stretch No	CL	CM	CH	PL	PM	PH	RL	RM	RH	PAL	PAM	PAH	RUL	RUM	RUH	EL	EM	EH	Code	IRI	RI	Rank
M-1	0.0	0.0	0.0	0.0	19.0	208.4	0.0	102.1	2510.0	31.5	266.0	122.5	60.0	60.0	0.0	127.5	56.3	6.8	8	7.32	22.53	2
M-2	35.0	157.0	0.0	0.0	22.6	346.2	0.0	690.5	1819.1	0.0	210.0	0.0	100.0	50.0	0.0	133.8	25.8	0.0	8	7.55	18.79	5
M-3	35.0	0.0	0.0	0.0	9.6	17.2	0.0	1207.3	1652.1	0.0	455.3	0.0	0.0	0.0	0.0	123.5	0.0	0.0	8	6.06	11.49	27
M-4	72.9	70.0	70.0	4.4	76.9	264.0	328.1	35.0	1703.8	0.0	800.0	0.0	0.0	0.0	0.0	74.6	0.0	0.0	8	7.47	18.83	4
M-5	338.3	280.0	490.0	11.7	27.3	124.3	61.3	276.2	1020.1	0.0	658.4	0.0	80.0	0.0	0.0	156.3	16.5	0.0	8	6.54	15.64	12
M-6	1.5	315.0	0.0	4.4	19.8	119.1	105.0	186.7	950.3	17.5	1649.7	0.0	90.0	120.0	0.0	49.6	0.0	0.0	8	7.36	14.78	16
M-7	0.0	0.0	140.0	0.0	1.8	0.0	2440.3	595.0	140.0	70.0	35.0	0.0	120.0	60.0	0.0	0.0	0.0	0.0	8	5.12	8.15	43
M-8	0.0	0.0	0.0	0.0	0.0	68.3	1017.5	917.0	911.0	17.5	140.0	0.0	0.0	0.0	0.0	427.8	0.0	0.0	8	5.4	10.23	35
M-9	0.0	0.0	0.0	0.0	10.2	51.9	420.0	1471.9	1300.5	0.0	157.5	0.0	0.0	0.0	0.0	87.3	0.0	0.0	8	5.85	11.42	28
M-10	0.0	0.0	0.0	0.0	8.0	25.9	756.0	1222.1	1015.5	0.0	472.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	8	5.81	10.39	33
M-11	152.3	0.0	0.0	0.0	18.6	0.0	738.5	2220.2	203.0	0.0	122.5	0.0	50.0	60.0	0.0	0.0	0.0	0.0	8	5.4	9.62	40
M-12	140.0	0.0	0.0	0.0	3.6	0.0	3316.4	0.0	0.0	0.0	0.0	0.0	60.0	20.0	0.0	0.0	0.0	0.0	8	4.61	6.63	45
M-13	157.5	171.5	0.0	0.0	0.0	29.2	2846.3	80.5	182.0	0.0	0.0	0.0	80.0	0.0	0.0	0.0	0.0	0.0	8	4.84	6.93	44
M-14	0.0	0.0	0.0	0.0	22.6	104.0	1941.5	507.1	402.4	161.0	150.5	0.0	90.0	0.0	0.0	145.4	25.7	0.0	8	5.58	11.58	26
M-15	0.0	0.0	0.0	0.0	25.5	109.4	325.5	0.0	1300.4	171.5	1350.7	0.0	100.0	20.0	0.0	154.2	12.6	0.0	8	7.03	14.96	14
S-1	0.0	0.0	0.0	21.9	42.0	259.0	0.0	564.5	514.8	245.0	1100.3	490.0	320.0	0.0	0.0	88.5	46.3	0.0	5	7.81	23.73	1
S-2	0.0	0.0	0.0	11.1	33.5	203.9	312.1	301.3	1198.2	70.0	802.1	325.2	180.0	60.0	0.0	76.8	65.8	0.0	5	7.3	20.85	3
S-3	0.0	0.0	0.0	5.8	11.7	45.2	535.2	1157.9	439.0	0.0	815.6	306.6	220.0	0.0	0.0	93.5	0.0	0.0	5	6.2	13.43	19
S-4	0.0	0.0	0.0	5.8	43.8	39.4	236.3	728.1	940.2	17.5	700.0	595.0	180.0	0.0	0.0	84.6	4.5	0.0	5	6.57	18.05	6
S-5	0.0	385.0	0.0	0.0	14.6	35.0	688.3	519.2	142.9	0.0	1122.1	350.0	120.0	140.0	0.0	96.3	46.5	0.0	5	6.31	17.03	8
S-6	700.0	350.0	140.0	0.0	16.0	19.0	1311.8	208.5	65.6	0.0	525.0	0.0	80.0	160.0	0.0	59.6	5.3	0.0	5	5.39	12.21	23
S-7	964.0	420.0	329.6	0.0	5.8	48.3	1247.4	172.1	195.4	0.0	0.0	17.5	140.0	120.0	0.0	0.0	0.0	0.0	5	5.24	11.17	29
S-8	687.5	280.0	514.5	212.9	14.0	38.8	1094.3	157.5	123.2	0.0	17.5	0.0	100.0	230.0	0.0	226.8	0.0	0.0	5	5.95	15.43	13

Stretch No	CL	CM	CH	PL	PM	PH	RL	RM	RH	PAL	PAM	PAH	RUL	RUM	RUH	EL	EM	EH	Code	IRI	RI	Rank
S-9	350.0	385.0	702.9	0.0	2.9	68.0	1181.0	482.0	0.0	0.0	122.5	0.0	150.0	120.0	0.0	93.3	12.4	0.0	5	5.55	13.48	18
S-10	350.0	455.0	875.0	0.0	14.6	63.3	414.2	1038.0	0.0	0.0	210.0	0.0	200.0	0.0	0.0	0.0	0.0	0.0	5	5.69	13.62	17
S-11	157.5	770.0	1312.5	0.0	0.0	23.3	800.5	210.0	116.7	0.0	52.5	0.0	130.0	0.0	0.0	0.0	0.0	0.0	5	5.38	12.50	22
S-12	35.0	560.0	507.5	0.0	0.0	0.0	353.0	820.5	175.0	0.0	910.0	0.0	180.0	0.0	0.0	43.5	23.2	0.0	5	5.79	12.66	21
S-13	105.0	665.0	647.5	0.0	0.0	0.0	730.0	402.5	0.0	0.0	105.0	735.0	160.0	0.0	0.0	34.6	0.0	0.0	5	5.63	14.95	15
S-14	102.8	315.0	1347.5	0.0	0.0	2.2	728.5	175.0	0.0	0.0	420.0	140.0	80.0	150.0	0.0	132.4	35.7	0.0	5	5.8	15.78	10
S-15	735.0	857.5	280.0	0.0	0.0	0.0	1325.5	0.0	0.0	0.0	0.0	105.0	88.0	90.0	0.0	113.2	12.6	0.0	5	4.78	11.74	25
N-1	0.0	0.0	0.0	0.0	0.0	0.0	3360.0	0.0	0.0	0.0	0.0	0.0	160.0	120.0	30.0	0.0	0.0	0.0	2	4.48	15.80	9
N-2	0.0	0.0	0.0	0.0	0.0	0.0	3390.0	0.0	0.0	0.0	0.0	0.0	120.0	130.0	0.0	0.0	0.0	0.0	2	4.35	10.37	34
N-3	0.0	0.0	0.0	0.0	0.0	0.0	2310.0	0.0	0.0	1085.0	0.0	0.0	260.0	0.0	0.0	0.0	0.0	0.0	2	4.77	9.74	39
N-4	0.0	0.0	0.0	0.0	0.0	0.0	2070.0	0.0	0.0	920.0	350.0	0.0	380.0	0.0	0.0	0.0	0.0	0.0	2	5.15	10.66	31
N-5	0.0	0.0	0.0	0.0	0.0	0.0	2871.5	350.0	0.0	208.5	0.0	0.0	160.0	0.0	0.0	0.0	0.0	0.0	2	4.29	9.23	42
N-6	0.0	0.0	0.0	0.0	0.0	0.0	2638.5	0.0	0.0	561.5	0.0	0.0	250.0	220.0	30.0	0.0	0.0	0.0	2	5.06	17.55	7
N-7	0.0	0.0	0.0	0.0	0.0	0.0	2785.0	0.0	0.0	205.0	350.0	0.0	220.0	150.0	20.0	0.0	0.0	0.0	2	4.98	15.76	11
N-8	0.0	175.0	0.0	0.0	0.0	0.0	2420.0	0.0	0.0	805.0	0.0	0.0	190.0	0.0	0.0	0.0	0.0	0.0	2	4.54	10.11	36
N-9	0.0	0.0	0.0	0.0	0.0	0.0	2112.0	0.0	0.0	610.0	700.0	0.0	130.0	0.0	0.0	0.0	0.0	0.0	2	4.9	10.49	32
N-10	0.0	0.0	0.0	0.0	0.0	0.0	2010.0	0.0	0.0	1080.0	350.0	0.0	140.0	0.0	0.0	0.0	0.0	0.0	2	4.86	10.03	38
N-11	0.0	0.0	0.0	0.0	0.0	0.0	2155.0	0.0	0.0	600.0	630.0	0.0	150.0	130.0	0.0	0.0	0.0	0.0	2	5.17	11.84	24
N-12	0.0	0.0	0.0	0.0	0.0	0.0	1872.5	0.0	0.0	0.0	1507.5	0.0	160.0	140.0	0.0	0.0	0.0	0.0	2	5.63	13.29	20
N-13	0.0	0.0	0.0	0.0	0.0	0.0	2325.0	0.0	0.0	375.0	0.0	0.0	180.0	60.0	0.0	0.0	0.0	0.0	2	4.16	9.57	41
N-14	0.0	0.0	0.0	0.0	0.0	0.0	2130.0	0.0	0.0	460.0	0.0	0.0	190.0	80.0	0.0	0.0	0.0	0.0	2	4.22	10.04	37
N-15	0.0	0.0	0.0	0.0	0.0	0.0	3205.0	0.0	0.0	0.0	105.0	0.0	320.0	120.0	0.0	0.0	0.0	0.0	2	4.71	10.87	30

LEGEND: CL = Low Severity Cracking CM= Medium Severity Cracking CH= High Severity Cracking PL= Low Severity Potholes PM= Medium Severity potholes PH= High Severity Potholes RL= Low severity Raveling RM= Medium Severity Raveling RH= High Severity Raveling PAL= Low Severity Patching PAM= Medium Severity Patching PAH= High Severity Patching RUL= Low Severity Rutting RUM= Medium Severity Rutting RUH= High Severity Rutting EL= Low Severity Edge Failure EM= Medium Severity Edge Failure EH= High Severity Edge Failure RI= Ranking Index

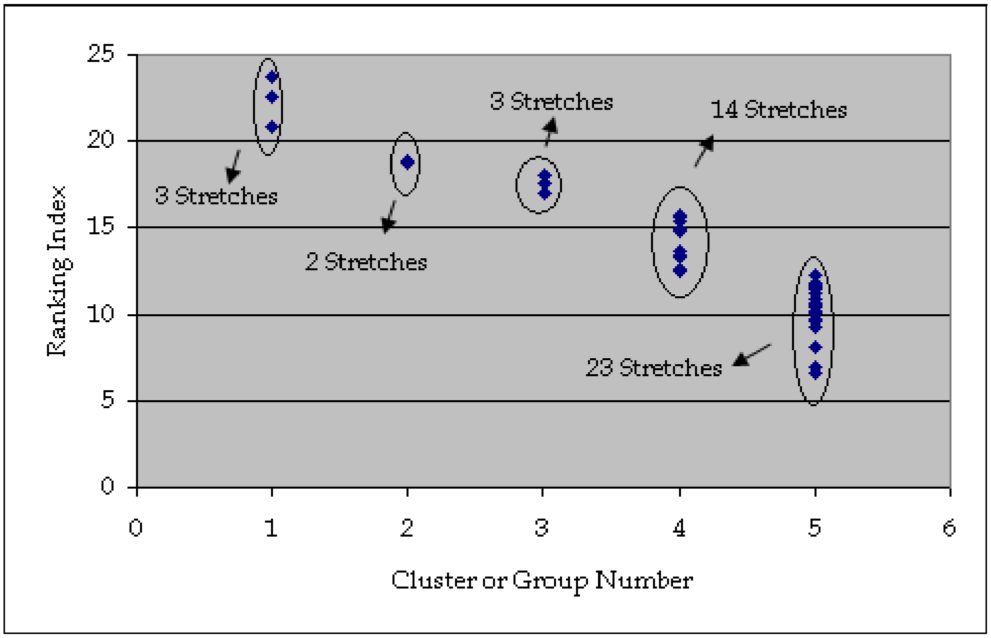


Fig 7.9: Pavement Stretches in Different Groups

The stretch numbers falling in different groups has been presented in Table 7.4.

Table 7.4: Stretches in Various Groups after Iteration 1

Group Number	Stretch No.	No. of stretches from Different Functional Class of Highway			Total Number of Stretches
		MDR	SH	NH	
1	S-1, M-1, S-2	1	2	Nil	3
2	M-4, M-2	1	1	Nil	2
3	S-4, N-6, S-5	Nil	2	1	3
4	N-1, S-14, N-7, M-5, S-8, M-6, S-13, M-15, S-10, S-9, S-3, N-12, S-12, S-11,	3	8	3	14
5	S-6, S-15, M-3, M-14, N-11, M-9, S-7, N-15, N-2, M-8, N-9, N-14, M-10, N-4, N-13, M-11, N-8, N-10, N-5, N-3, M-7, M-13, M-12	10	2	11	23

It may be observed that, out of the three stretches falling in group number 1, two are from SH and one from MDR. There was no stretch from NH in group numbers 1 and 2, which gets top priority. Most of the NH stretches were in the fifth group with the last priority in maintenance. It reveals that the condition of the NH stretches was good. This was expected as separate funds are allotted from the Central Government for timely maintenance of NHs.

The next step after grouping is the decision on the maintenance of the stretches. This would depend on the availability of funds. Since the budget may vary widely, it was decided to carryout the analysis by varying the budget from Rupees 10 to 50 lakhs with a uniform increment of 10 lakhs. As already discussed, it is possible to choose any one of the two types of maintenance options such as construction of overlay or repairing of distress parameters. According to the decision the software predicts the funds required for maintenance and corresponding changes in roughness levels. In this example, treatments and unit cost required to repair them as suggested in the Table 7.2 has been considered.

Initially, a budget of Rupees 10 lakhs was considered and different maintenance options were selected randomly and the corresponding change in roughness levels were studied. As shown in Table 7.4, three stretches namely M-1, S-1 and S-2 were in the first group. As the potholes have very high contribution on roughness as well as they cause discomfort to the road users, it was decided to repair the potholes of all the three severity levels on all three stretches. The funds required were Rupees 1, 15, 115 respectively. Since, funds were still available, the steps were repeated until it is exhausted.

After the second iteration, the stretches falling into various groups are shown in Table 7.5. It can be observed from the table that the stretches M-2 and M-4 fell in the first groups, which were in second group after the first Iteration.

After repairing all the potholes, the stretches S-1, S-2 fell in third group and the stretch M-1 fell in second group after the second iteration.

Table 7.5: Stretches in Various Groups after Iteration 2

Group Number	Stretch No.	No. of stretches from Different Functional Class of Highway			Total Number of Stretches
		MDR	SH	NH	
1	R-4, MDR-2	2	Nil	Nil	2
2	S-4, N-6, M-1,S-5	1	2	1	4
3	N-1, S-1, S-14, N-7, M-5, S-8, S-2, M-15, S-13, M-6, S-10, S-9, S-3,N-12, S-12, S-11	3	10	3	16
4	S-6, N-11, S-15, M-14, M-3, M-9, S-7, N-15, N-4, N-9, M-10, N-2, M-8, N-8, N-14, N-10, N-3, M-11, N-13, N-5	6	3	11	20
5	M-7, M-13, M-12	3	Nil	Nil	3

Number of the stretches falling in different groups after the second iteration is as shown in Fig 7.10. Once again the potholes of three severity levels were selected for repair and the total budget utilized after the second iteration was Rupees 2, 93, 991. As still budget was available, the stretches were grouped and prioritized again. Stretches falling in different groups after third iteration is shown in Table 7.6. It might be observed that 15 stretches from different functional classes were falling in first group. Also it could be observed that the potholes presented in stretches, namely S-1, S-2 and M-1 repaired after the first iteration were again coming back in the first group. The stretches namely M-2 and M-4, which were repaired after the second iteration is now falling in second and third, group respectively.

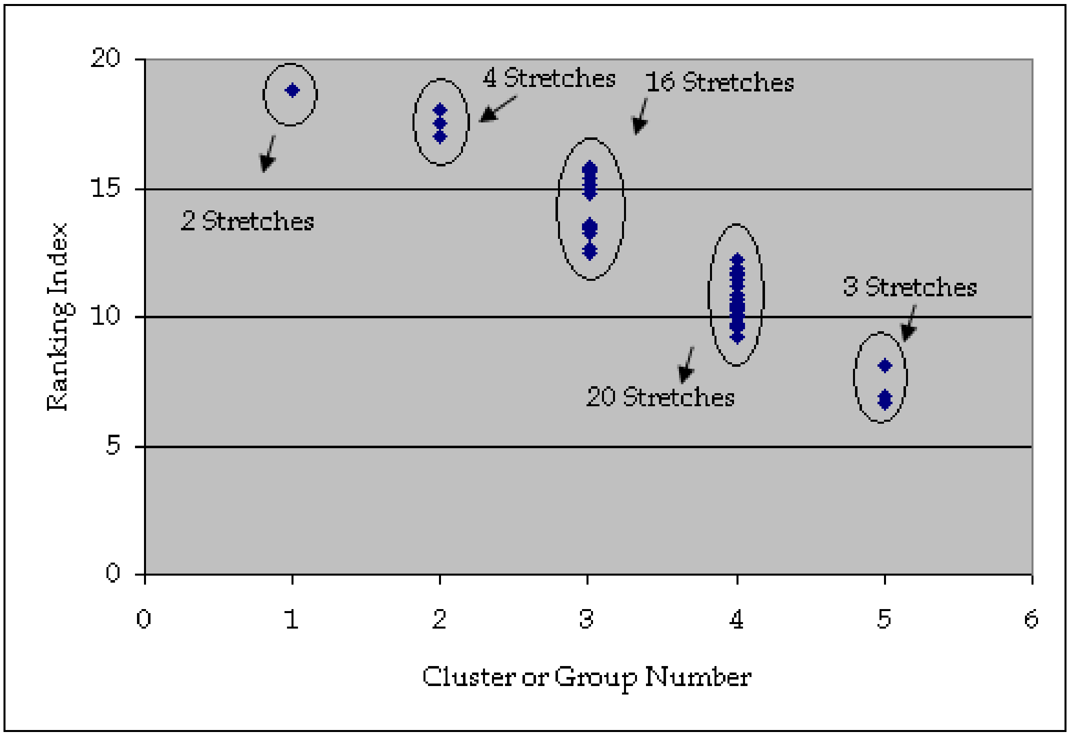


Fig 7.10: Pavement Stretches in Different Groups after Iteration 2

Table 7.6: Stretches in Various Groups after Iteration 3

Group Number	Stretch No.	No. of stretches from Different Functional Class of Highway			Total Number of Stretches
		MDR	SH	NH	
1	S-4, N-6, M-1, S-5, N-1, S-1, S-14, N-7, MDR-5, S-8, S-2, M-15, S-13, M-6, S-10	4	8	3	15
2	S-9, S-3, N-12, S-12, S-11, M-2, S-6, N-11, S-15, M-14, M-3, M-9	4	6	2	12
3	S-7, N-15, N-4, N-9, M-10, N-2, M-8, M-4, N-8, N-14, N-10, N-3, M-11, N-13	4	1	9	14
4	N-5, M-7, M-13, M-12	3	Nil	1	4

Number of stretches fell in different groups after the third iteration has been shown in Fig. 7.11.

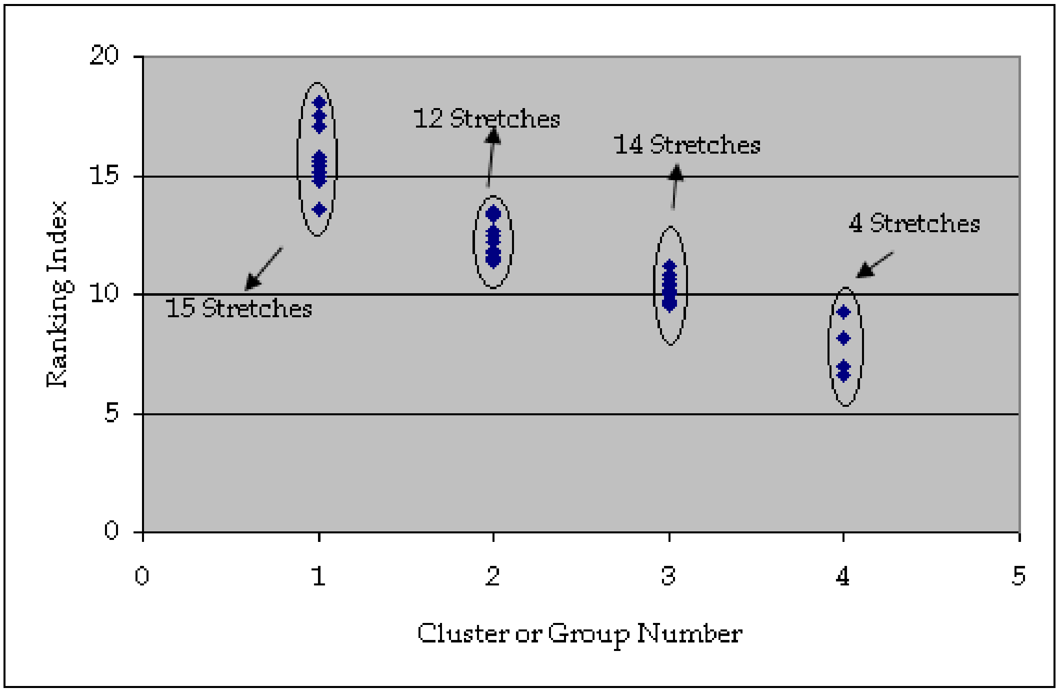


Fig 7.11: Pavement Stretches in Different Groups after Iteration 3

This process would be continued until the budget gets exhausted. In this example available budget of Rupees 10 lakhs were used after seven iterations. After each iteration, different types of maintenance options were implemented. The types of maintenance options in all seven iterations and the cost have been presented in Table 7.7. It is to be noted here that the selection of kind of maintenance option was purely based on the user and the availability of funds.

It might be noted from the table that after 5th iteration only high severity raveling was selected. It was due to the fact that stretch number M-1 only fell in the first group and other distresses present on that stretches were already repaired in previous iterations.

Table 7.7: Different Types of Maintenance Options Selected and Budget Utilized

Iteration Number	Type of Maintenance Options Selected	Cost	Cumulative Cost
1	Potholes of all three severities	154115	154115
2	Potholes of all three severities	139876	293991
3	Potholes of all three severities and low severity raveling	331028	625019
4	Potholes and Patching of all three severities	265913	890932
5	Rutting of all three severities	9108	900040
6	High severity raveling	45179	945219
7	Potholes of all three severities and low level patching	48359	993578

It is also to be noted here that the user needs to select the distresses carefully so that the maintenance decision would improve the roughness as much as possible. Summary of the cost on various stretches for repairing different distresses, initial and final roughness values, PSI values have been presented in Table 7.8.

Table 7.8: Summary of Budget Required For Repairing the Distresses Present in Various Stretches and Changes in Roughness Levels

Stretch No	CL	CM	CH	PL	PM	PH	RL	RM	RH	PAL	PAM	PAH	RUL	RUM	RUH	EL	EM	EH	Total Cost	Initial IRI	Final IRI	PSI
M-1	0	0	0	0	2749.2	42717.9	0	0	45179.6	567	22610	17762.5	288	432	0	0	0	0	132306	7.3	3.1	2.87
M-2	0	0	0	0	3277	70971	0	0	0	0	0	0	0	0	0	0	0	0	74248	7.6	5.9	1.73
M-3	227.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	227.5	6.1	6.1	1.66
M-4	0	0	0	372.3	11143.3	54111.8	0	0	0	0	0	0	0	0	0	0	0	0	65627.4	7.5	5.9	1.70
M-5	0	0	0	991.95	3954.15	25485.6	551.25	0	0	0	0	0	0	0	0	0	0	0	30983	6.5	5.8	1.74
M-6	0	0	0	372.3	2875.35	24425.8	945	0	0	0	0	0	0	0	0	0	0	0	28618.4	7.4	6.7	1.49
M-7	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.1	5.1	1.97
M-8	0	0	0	0	0	0	0	0	0	315	0	0	0	0	0	0	0	0	315	5.4	5.4	1.88
M-9	0	0	0	0	1480.45	10643.6	0	0	0	0	13387.5	0	0	0	0	0	0	0	25511.6	5.9	5.4	1.88
M-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.8	5.8	1.74
M-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.4	5.4	1.87
M-12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.6	4.6	2.16
M-13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	4.8	2.07
M-14	0	0	0	0	3277	21315.9	17473.5	0	0	0	0	0	0	0	0	0	0	0	42066.4	5.6	4.2	2.33
M-15	0	0	0	0	3700.4	22422.9	2929.5	0	0	0	0	0	0	0	0	0	0	0	29052.8	7	6.3	1.60
S-1	0	0	0	1859.8	6090	53095	0	0	0	4410	0	0	1536	0	0	0	0	0	66990.8	7.8	5.6	1.80
S-2	0	0	0	945.2	4863.3	41795.4	0	0	0	1260	0	0	0	0	0	0	0	0	48863.9	7.3	6.1	1.64
S-3	0	0	0	495.55	1692.15	9268.05	0	0	0	0	69328.6	44454.1	0	0	0	0	0	0	125238	6.2	4.6	2.18
S-4	0	0	0	495.55	6343.75	8072.9	2126.25	0	0	315	0	0	0	0	0	0	0	0	17353.5	6.6	6.1	1.66
S-5	0	0	0	0	2114.1	7175	6194.25	0	0	0	0	0	576	1008	0	0	0	0	17067.4	6.3	5.3	1.92
S-6	0	0	0	0	2325.8	3886.8	0	0	0	0	44625	0	0	0	0	0	0	0	50837.6	5.4	4.6	2.17
S-7	0	0	0	0	845.35	9895.35	0	0	0	0	0	2537.5	0	0	0	0	0	0	13278.2	5.2	5	2.03
S-8	0	0	0	18098.2	2030	7951.95	9848.97	0	0	0	0	0	0	0	0	0	0	0	37929.1	6	4.6	2.17

Stretch No	CL	CM	CH	PL	PM	PH	RL	RM	RH	PAL	PAM	PAH	RUL	RUM	RUH	EL	EM	EH	Total Cost	Initial IRI	Final IRI	PSI
S-9	0	0	0	0	423.4	13931.8	10629	0	0	0	0	0	0	0	0	0	0	0	24984.2	5.6	4.7	2.12
S-10	0	0	0	0	2114.1	12974.5	3727.53	0	0	0	0	0	0	0	0	0	0	0	18816.1	5.7	5.2	1.95
S-11	1023.7	6930	15750	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	23703.8	5.4	3.8	2.51
S-12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.8	5.8	1.74
S-13	682.5	5985	7770	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	14437.5	5.6	4.7	2.14
S-14	0	0	0	0	0	448.95	6556.5	0	0	0	0	0	384	1080	0	0	0	0	8469.45	5.8	5	2.02
S-15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	4.8	2.10
N-1	0	0	0	0	0	0	30240	0	0	0	0	0	0	0	0	0	0	0	30240	4.5	3.1	2.87
N-2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.4	4.4	2.27
N-3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.8	4.8	2.10
N-4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.2	5.2	1.96
N-5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.3	4.3	2.29
N-6	0	0	0	0	0	0	23746.5	0	0	10107	0	0	1200	1584	1020	0	0	0	37657.5	5.1	2.4	3.23
N-7	0	0	0	0	0	0	25065	0	0	3690	0	0	0	0	0	0	0	0	28755	5	3.6	2.58
N-8	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.5	4.5	2.19
N-9	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.9	4.9	2.05
N-10	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.9	4.9	2.07
N-11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.2	5.2	1.95
N-12	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	5.6	5.6	1.80
N-13	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.2	4.2	2.35
N-14	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.2	4.2	2.32
N-15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.7	4.7	2.12
	1933.7	12915	23520	23630.9	61298.8	440590	140033	0	45179.6	20664	149951	64754.1	3984	4104	1020	0	0	0	**993578**			

A graph shown in Fig 7.12 was plotted to observe the change in roughness levels before and after maintenance of pavement stretches, where the stretch numbers 1 to 15 represent M-1 to M-15, 16 to 30 represents S-1 to S-15 and the stretch number 31 to 45 represents N-1 to N-15.

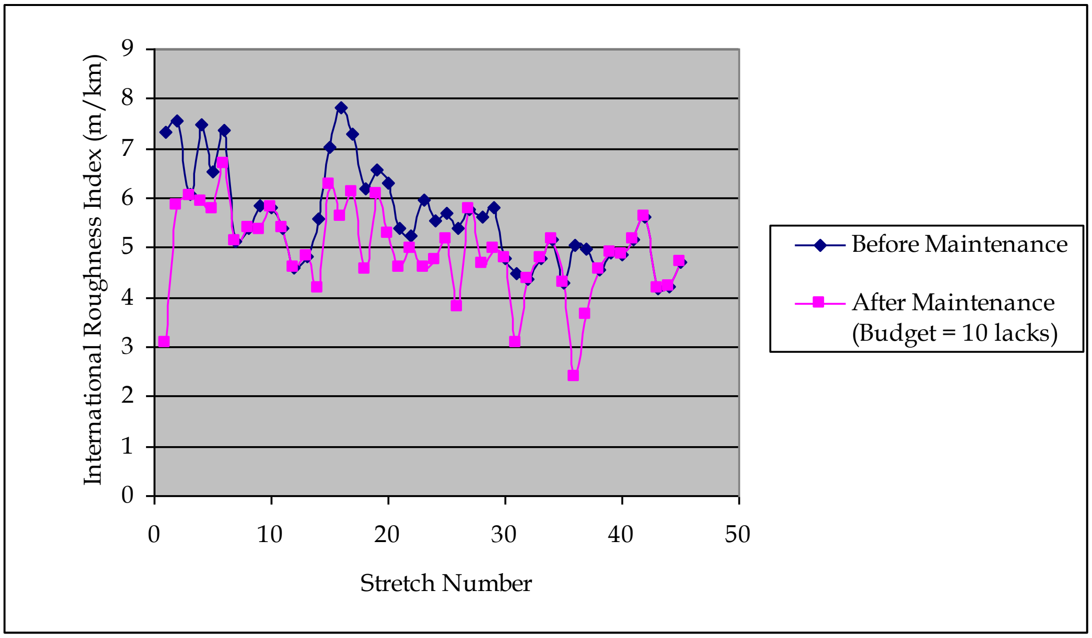


Fig 7.12: Change in Roughness Levels before and After Maintenance Due to Selection of Various Maintenance Options on Different Stretches

It might be observed from the Fig 7.12 that, the roughness levels on majority of stretches changed due to repair work taken up under maintenance plan. However, due to the limited budget few stretches were not considered for repair and accordingly roughness levels did not change. Also it may be observed that there was a drastic change in roughness levels on a few stretches namely M-1, N-1 and N-36 after the maintenance. This is due to the fact that after little iteration these stretches were coming in the high priority group again and again.

It was also observed that the changes are in roughness levels after spending a budget of 10 lakhs for repairing all the distresses present on the stretches which are in top priority group. As discussed above after the first iteration stretches namely M-1, S-1 and S-2 were in the first group, hence, all the distresses present over it were repaired. The amount required for the same was Rupees 5, 92, 967. Since the funds were still available the stretches those proposed to be repaired were grouped and prioritized again. After the second iteration the stretches namely M-2 and M-4 fell in the first group and it was decided to repair all the distresses. Total cost after the second iteration was Rupees 9, 02, 258 and still budget of Rupees 97,742 was available. All the stretches were prioritized and grouped again and the stretches in first group were considered for repair. The balance amount was not sufficient to take the repair work for all the distresses in all the stretches. Thus, the distresses to be repaired were chosen by trail and error process so that the budget is just exhausted. The change in roughness values in all the stretches after incorporating all the maintain decisions including all the iterations is shown in Fig. 7.13.

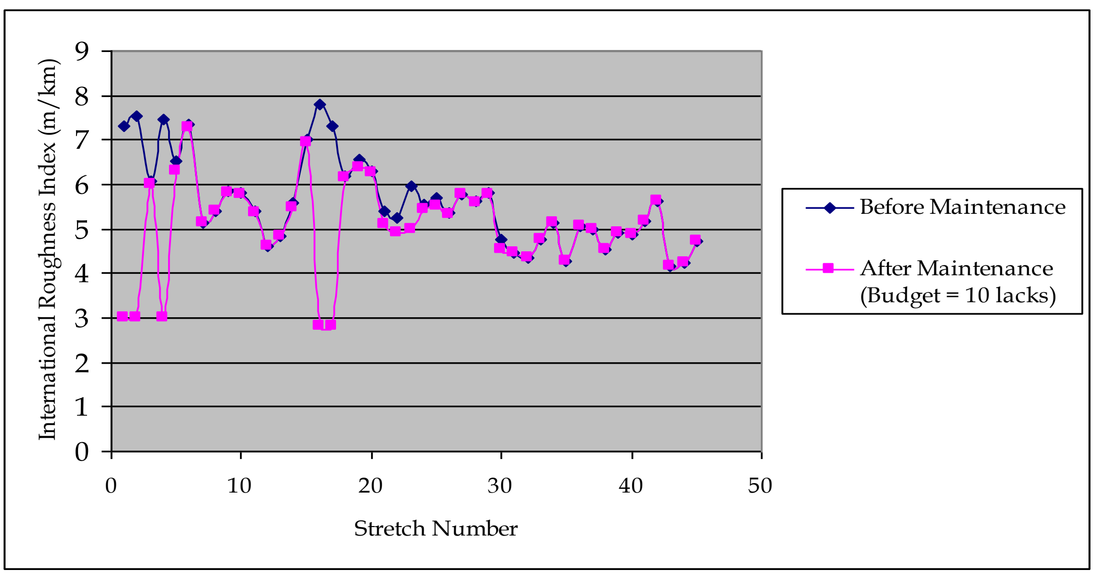


Fig 7.13: Change in Roughness Values before and After Repairing all the Distresses Present on the Stretches which were in the Top Priority Group

It might be observed that only in 4 stretches roughness changed drastically and in all other stretches it remained the same, thus showing the limitation of such maintenance management decision.

The above discussion was based on an assumption that the available budget was rupees 10 lakhs. However, the amount may vary depending on the budgetary allocation in a particular year. To study the change in pavement roughness in each stretch in a network when the allocated fund was varied between rupees 10 to 50 lakhs with an uniform increment of rupees 10 lakhs, predicted roughness in all the stretches with different budgets were determined (Fig 7.14)

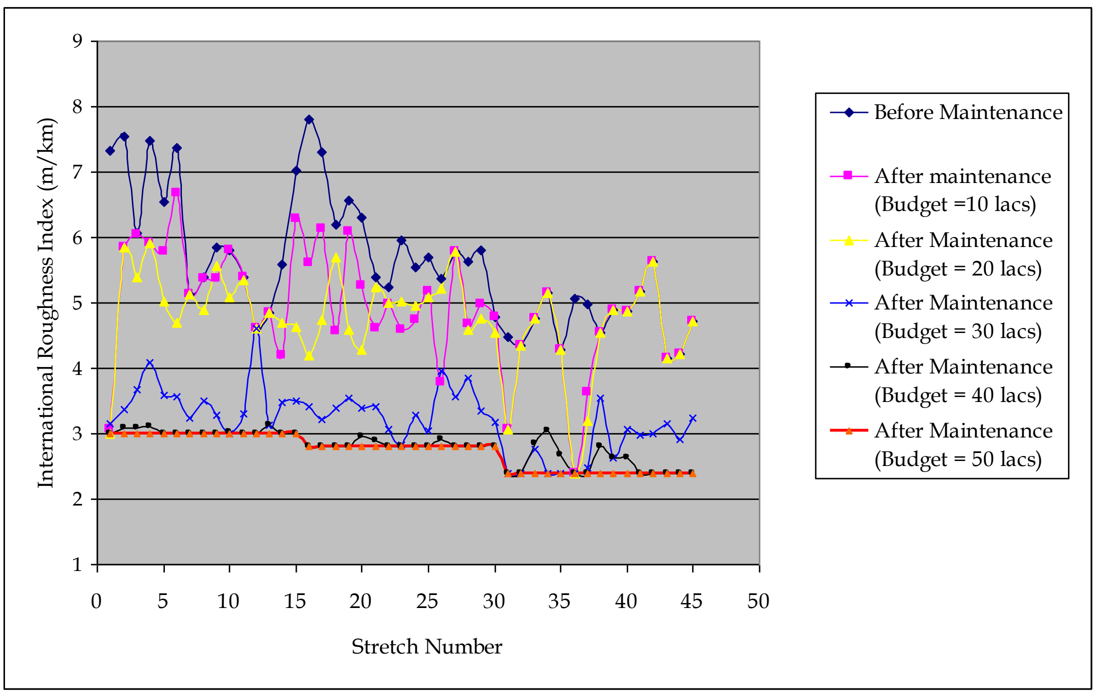
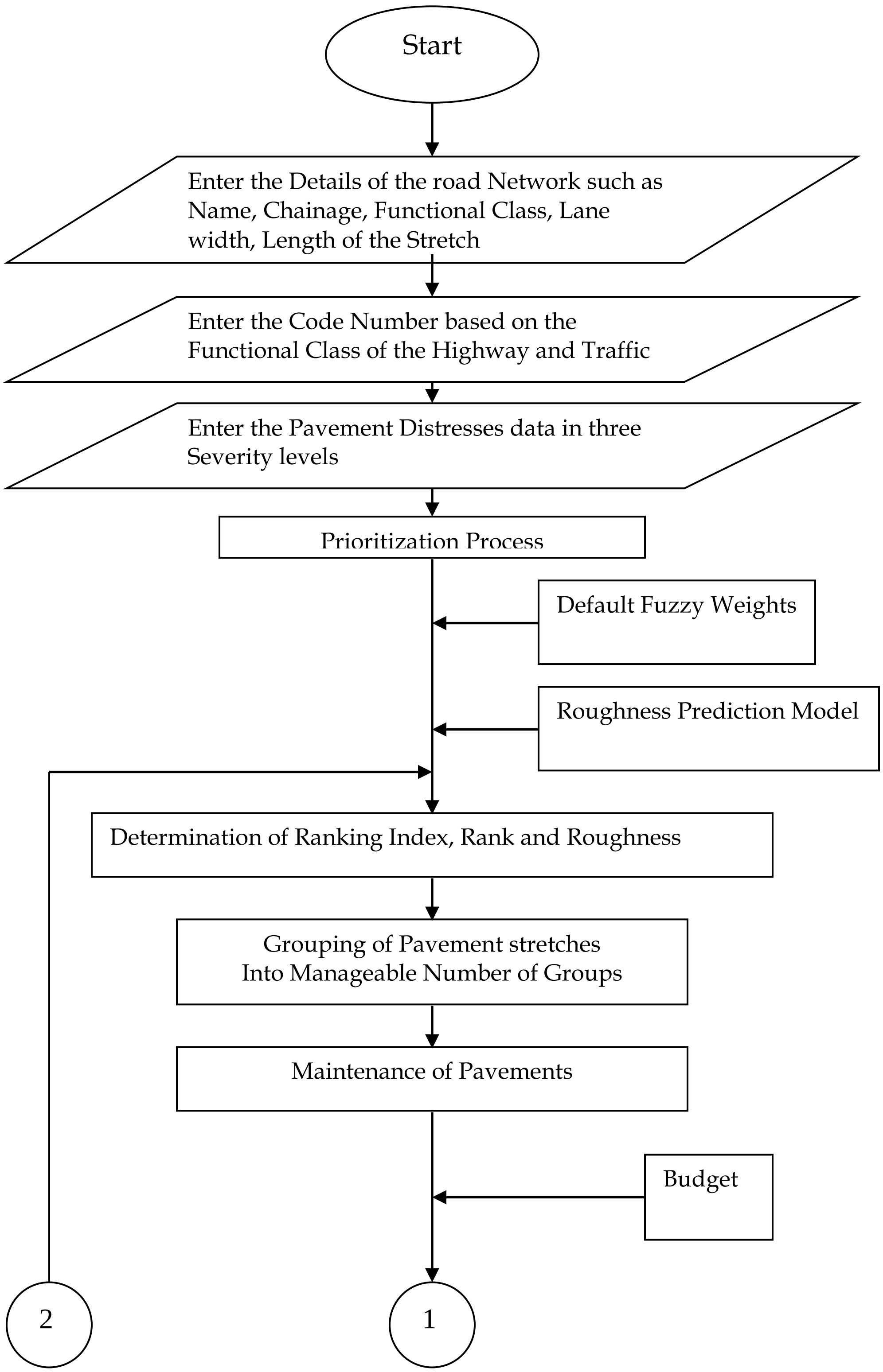


Fig 7.14: Change in Roughness Levels under Different Budget Scenario

It might be noted from the graph that when the budget was rupees 30 lakhs the roughness was less than 4 m/km in all the stretches except in one stretch. When the budget was raised to 40 lakhs, the roughness was equal to or less than 3 m/km in all the stretches. However, to bring the roughness to its initial roughness of 3 m/km on stretches of MDR, 2.8 m/km on stretches of SH and 2.4 m/km on stretches of NH, there was a need to spend about rupees 42 lakhs for all the 45 stretches. A flow chart shown in Fig 7.15 explains the stages involved in the software.



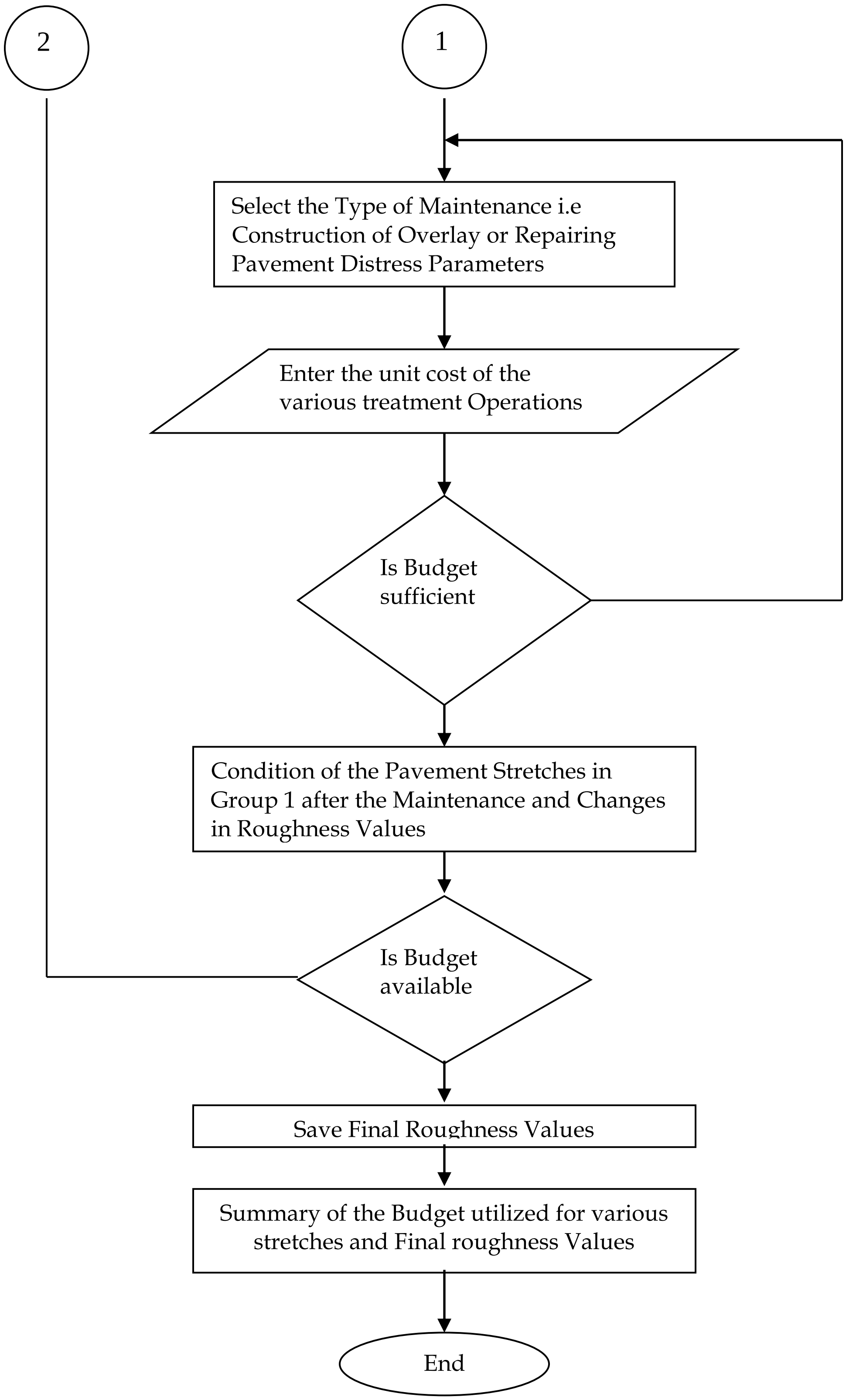


Fig 7.15 Flow Chart for Developing Software for Maintenance of Pavement Stretches at Network Level

7.4 SUMMARY

In the present chapter, various stages involved in the development of the user friendly software have been discussed. Also the various types of treatments for repairing distresses and their unit cost was presented. In addition, the application of software was explained with an example.

CHAPTER 8

FINDINGS, CONCLUSIONS, RECOMMENDATIONS AND SCOPE FOR FURTHER INVESTIGATION

8.1 GENERAL FINDINGS

Many of the developing countries such as India have failed to maintain the roads properly due to lack of sufficient funds and also inability to use available funds judiciously and effectively in the absence of proper maintenance management system. Though a number of maintenance management systems are available in the form of comprehensive packages, most of them require huge database, such as history of individual pavement stretches and time series data on pavement conditions. It is difficult to get such systematic data in India. Thus it was felt necessary to develop a Pavement Maintenance Management System (PMMS), which would follow the exiting maintenance pattern of the Public Works Department (PWD) of the state governments and strengthen them. A few maintenance management systems predict the roughness after construction of the overlay but none of them have included the prediction of roughness after repairing individual distresses as a part of maintenance activity. To do this, it is necessary to develop the relationship between roughness and pavement distress parameters. Also it is necessary to develop an user friendly software for taking appropriate maintenance decisions, distributing available funds logically and predicting roughness after the maintenance activity. The following are the general finding from the present research work.

- It has been observed that roughness is usually manifested as a combined effect of different individual pavement deterioration parameters such as cracking, potholes, raveling, patching and rutting (Chapter-2, Sub Section-2.2). Number of researchers have concentrated in the direction of developing roughness progression models by considering different combinations of influencing parameters, which were collected over a period of time. However, enough research has not been carried out for developing models, which are capable of expressing the roughness at a given point of time as a function of noticeable distresses (Chapter-2, Sub Section -2.2.1).

- It was observed that a number of researchers had developed relations between Present Serviceability Index (PSI) and distresses, however, these relationships may not be suitable for Indian conditions as they have neglected few distress parameters which are quite common on Indian roads. It has also been noticed that the relationship developed between roughness and PSI by Paterson (1986) is more appropriate to predict the PSI from the roughness (Chapter-2, Sub Section -2.2.4).

- Among the various available prioritization techniques, fuzzy multi criteria approach was found to be one of the most appropriate techniques for the present investigation due to the presence of uncertainty (Chapter-2, Sub Section -2.3.4).

- It is difficult to maintain the network comprising large number of stretches based on the individual ranking. In such situations it would be practical to take maintenance decisions on a group or cluster of stretches having similar distress characteristics. It has been observed that K-means technique is the most suitable for grouping of pavement stretches. (Chapter-2, Sub Section -2.4).

- While measuring the roughness using Bump Integrator, it was found difficult to maintain the standard operating speed of 32 km/hr due to poor pavement condition and heterogeneity of traffic (Chapter-4, Sub Section -4.1).

- It was observed that the weights of the distress parameters obtained from various experts through the questionnaire survey in linguistic variables were quite consistent (Chapter-4, Sub Section -4.6).

- While determining the unevenness at various operating speeds it was observed that roughness was decreasing with increase in operating speed of the Bump Integrator on uneven surfaces (Unevenness Index is more than 2500 mm/km) , but it was not varying much on even surfaces (Unevenness Index is less than 2500 mm/km). Roughness was very sensitive to the operating speed on uneven surfaces (Chapter-5, Sub Section -5.3).

- Models developed for converting the unevenness index collected at various operating speeds to the standard speed of 32 km/hr could be used with good accuracy (Chapter-5, Sub Section -5.3.1).

- On the basis of the data collected on various freshly overlaid pavements, it was observed that the average initial UI value on National Highway was 1750 mm/km (IRI=2.4 m/km), on State Highway it was 2025 mm/km (IRI=2.8m/km) and on Major District Roads it was 2225 mm/km (IRI=3.0 m/km) (Chapter-5, Sub Section -5.4.2)

- Model developed between roughness and distress parameters would predict the roughness with good accuracy. From this model, it was found that contribution of potholes of all severities was significant on roughness; whereas the contribution of low and medium severity cracking and rutting were not significant (Chapter-5, Sub Section-5.4.5).

- Though patching is a treatment for distresses, it is also contributing to roughness due to the fact that in most of the cases it wasn't being done according to the standard methods and there was a level difference between existing pavement and patched surface (Chapter-5, Sub Section -5.4.5).

- Relationship developed between roughness and pavement distress parameter could be used to study the impact of various individual distresses on the roughness (Chapter-5, Sub Section-5.5.1, 5.5.2). It could used to predict the changes in roughness levels based on the kind of maintenance work taken up (Chapter-5, Sub Section -5.6)

- It was observed from the roughness data collected over the entire width of the pavement along a number of longitudinal strips that there was not much variation in roughness on them in MDRs. However, it was found along the wheel paths on SHs and NHs (Chapter-5, Sub Section -5.7).

- Due to the presence of uncertainty in assessing weights, fuzzy approach was used for prioritization. However, this approach cannot be used when uncertainty is not involved (Article-6.2). The weights of distresses collected in linguistic variables could be easily converted into fuzzy numbers and this process would be quite useful if it is not possible to express the weights in quantifiable terms (Chapter-6, Sub Section -6.2.2).

- Experts gave high weightage on high severity pothole and less on low severity cracking (Chapter-6, Sub Section -6.2.2, Stage 6).

- Different approaches suggested for prioritizing of pavements are yielded same results hence, any of the suggested approach could be used (Chapter-6, Sub Section – 6.2.3)

- The developed algorithm for finding the Optimum Number of the Clusters (ONC) is suitable for grouping the pavement stretches into manageable number of groups (Chapter-6, Sub Section -6.3.2.1).

- Software developed for maintaining the pavement stretches at network level would be able to distribute the funds according to priority and also would predict the change in roughness after repairing the distresses. However, change in roughness levels on various stretches purely depends on the kind of maintenance decisions taken and the availability of funds (Chapter-7, Sub Section -7.3).

8.2 CONCLUSIONS

In the present study, an attempt has been made to develop a maintenance management system for flexible pavements so that the existing methods followed by the PWD of various states could be strengthened. Also a correlation has been developed between roughness and distresses and same was integrated in the maintenance system to study the impact of various distress parameters on roughness. Accordingly, a case study was conducted in two districts of Rajasthan in which various kinds of roads were considered such as NH, SH and MDR. On the basis of the study the following conclusions have been drawn.

- Besides the usual distresses such as rutting, patching and cracking considered by various researchers for determining the roughness, the contributions of potholes and raveling are quite predominant on Indian roads.

- The Unevenness Index values decrease significantly with the increase in operating speed of the Bump Integrator when the pavement condition is poor. The variation is insignificant on freshly overlaid pavements.

- The initial International Roughness Index (IRI) values on freshly overlaid pavements vary with the type of road with high category pavements having comparatively low IRI values.

- The contribution of any distress on the overall roughness of a pavement depends significantly on the severity and extent of the same.

- The contribution of potholes on the roughness of a pavement stretch is quite high whereas those of rutting and low severity cracking are not significant.

- Patching is done with the intension to improve the road condition, but due to poor workmanship it contributes significantly on the overall roughness.

- Using the relationship developed between roughness and distresses parameters in this study, the impact of various maintenance decisions on roughness could be determined and accordingly the best possible decision under the budgetary constraints could be taken.

- Due to regimented and high traffic volume, the wheel paths can be clearly identified on NHs. They are not that easily identifiable on MDRs and few SHs.

- The relationship between roughness and pavement distresses remains almost same irrespective of data being collected along the marked wheel path or over the entire width of the pavement.

- The fuzzy multi-criteria approach can be effectively applied for prioritizing the pavement stretches either individually or in groups.

- At the network level maintenance management, while each stretch might have different distresses of varying extent and severity, there is a need to use appropriate technique to arrive at the Optimum Number of Clusters (ONC) to group the stretches into manageable number.

- The software developed in the study can be used to take the maintenance decisions so as to distribute the available funds in a logical manner based on maintenance policy decided by the agency.

8.3 RECOMMENDATIONS

The following are some of the recommendations based on the experiences gained from the present research work.

- Public Works Department (PWD) engineers may use the software developed in this study for maintaining the pavements and for taking policy decisions on maintenance activities under budgetary constraints.

- The model developed for converting the roughness values collected at various speeds to the standard operating speed of 32 km/hr might be used on Indian roads.

- Since the availability of Bump Integrator is quite restricted with number of government organizations, the roughness values could be calculated from the data collected on pavement condition using the relationships developed in the study. However, proper definition of severity and extent of each distress needs to be developed so that they can be quantified easily by the field engineers.

- The Initial International Roughness Index (IRI) on freshly overlaid National Highway was 1750 mm/km (IRI=2.4 m/km), on State Highway it was 2025 mm/km (IRI=2.8m/km) and on Major District Roads it was 2225 mm/km (IRI=3.0 m/km). These values might be used for predicting total roughness on the various types of pavements if roughness due to distresses is known.

- The fuzzy approach followed for prioritization of pavement stretches can be used in any prioritizing process wherever uncertainty is involved.

8.4 SCOPE FOR FURTHER RESEARCH

While concluding the study, it was found that certain aspect of the study needs further attention. Those are presented below.

- All the distress parameters contributing to roughness could not be included in the present study and thus the other distresses such as bleeding, stripping and micro undulations can also be considered.

- The prioritization technique used in this study may also be applied for pavement management system by including other relevant factors such as conditions of shoulders, condition of side drains, geometric features and importance of road to the community.

- The software developed in this study mainly deals with repair of pavement distresses whereas overlay design part were not considered and thus there is a need to incorporate both in future study.

- Vehicle dynamics may also contribute in the measurement of road roughness, and hence may be included in the future research.

APPENDIX – 1

PHOTOGRAPHIC CLUES AND CUES FOR IDENTIFICATION OF DISTRESSES

CRACKING – SEVERITY LEVELS

(I) Low: Width of the cracking is less than 3mm

(II) Medium: Width of the cracking is greater than 3mm and less than 6mm

(III) High: Width of the cracking is greater than 6mm

POTHOLES - SEVERITY LEVELS

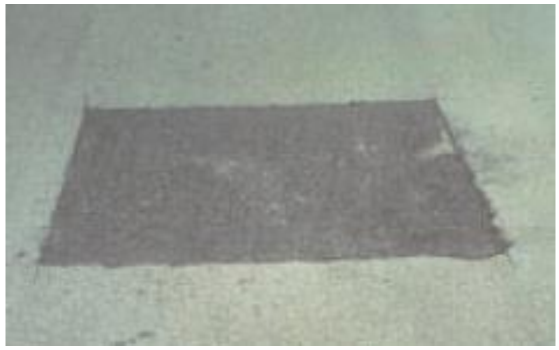
(I) Low: Depth of the pothole is less than 25mm

(II) Medium: Depth of the pothole is more than 25 mm and less than 50 mm

(III) High: Depth of the pothole is more than 50 mm

PATCHING - SEVERITY LEVELS

(I) Low: Patch has low severity distress of any type including rutting < 6 mm; pumping is not evident.



(II) Medium: Patch has moderate severity distress of any type or rutting from 6 mm to 12 mm; pumping is not evident.

(III) High: Patch has high severity distress of any type including rutting > 12 mm, or the patch has additional different patch material within it; pumping may be evident.

RAVELLING - SEVERITY LEVELS

(I) Low: The aggregate or binder has started to wear away but has not progressed significantly. The pavement appears only slightly aged and s lightly rough.

(II) Medium: The aggregate or binder has worn away and the surface texture is moderately rough and pitted. Loose particles may be present and fine aggregate is partially missing.

(III) High: The aggregate and/or binder have worn away significantly, and the surface texture is deeply pitted and very rough. Fine aggregate is essentially missing from the surface, and pitting extends to a depth approaching one half (or more) of the coarse aggregate size.

RUTTING – SEVERITY LEVEL

(I) **Low:** Barely noticeable, depth less than 6 mm

(II) **Medium:** Readily noticeable, depth more than 6 mm less than 25 mm

(III) **High:** Definite effect upon vehicle control, depth greater than 25 mm

EDGE FAILURE – SEVERITY LEVEL

(I) Low: Appearance of edge step with a few initial cracks on the bituminous surface along the edge portion of the carriageway

(II) Medium: Appearance of edge step with a number of interconnected high intensity cracks on the bituminous surface along the edge portion of the carriageway

(III) High: Permanent loss of part of carriageway and pothole formation along the edge portion

APPENDIX -2

Birla Institute of Technology and Science, Pilani

Civil Engineering Group

Proforma for Collecting Pavement Condition Data along the Wheel Path

Date and Time: **Name of the Road:**

Type of the Road: **Weather:** **Chainage:**

Length along the L.S	Width of the Lane = m (Along the direction of Traffic)			
	LWP		RWP	
10 – 20m				
0 – 10m				

CL=Low level cracking	CM=Medium level cracking	CH =High level cracking
PL=Low level potholes	PM=Medium level pothole	PH =High level potholes
RL=Low level raveling	RM=Medium level raveling	RH=High level raveling
PAL=Low level patching	PAM=Medium level patching	PAH=High level patching
RUL=Low level rutting	RUM=Medium level rutting	RUH=High level rutting
EL=Low level edge failure	EM=Medium level edge failure	EH=High level edge failure

40 – 50m				
30 – 40m				
20 – 30m				

Name of the Enumerator: **Signature:**

Birla Institute of Technology and Science, Pilani

Civil Engineering Group

Proforma for Collecting Pavement Condition Data over the Entire Width

Date and Time: **Name of the Road:**

Type of the Road: **Weather:** **Chainage:**

Length along the L.S	Width of the Lane = m (Along the direction of Traffic)
10 – 20m	
0 – 10m	

CL=Low level cracking CM=Medium level cracking CH =High level cracking

PL=Low level potholes PM=Medium level pothole PH =High level potholes

RL=Low level raveling RM=Medium level raveling RH=High level raveling

PAL=Low level patching PAM=Medium level patching PAH=High level patching

RUL=Low level rutting RUM=Medium level rutting RUH=High level rutting

EL=Low level edge failure EM=Medium level edge failure EH=High level edge failure

40 – 50m	
30 – 40m	
20 – 30m	

Name of the Enumerator: **Signature:**

APPENDIX – 3

BIRLA INSTITUTE OF TECHNOLOGY AND SCIENCE (BITS), PILANI
CIVIL ENGINEERING GROUP
EXPERT OPINION SURVEY

Kindly mark the appropriate cells with letter '**X**' indicating the level of influence of listed flexible pavement deterioration parameters on Functional / Structural Condition of a pavement stretch based on your vast experience as a researcher and road user. Necessary cues and clues are also provided for your ready reference. Thanks a lot for your cooperation and time.

Type of Failure	**Severity Level**	**Level of Influence on Functional Condition of the Pavement**				
		Negligible	**Low**	**Moderate**	**High**	**Very High**
Cracking	Low					
	Medium					
	High					
Potholes	Low					
	Medium					
	High					
Rutting	Low					
	Medium					
	High					
Patching	Low					
	Medium					
	High					
Ravelling	Low					
	Medium					
	High					
Edge Failure	Low					
	Medium					
	High					

Type of Failure	Severity Level	Level of Influence on Structural Condition of the Pavement				
		Negligible	Low	Moderate	High	Very High
Cracking	Low					
	Medium					
	High					
Potholes	Low					
	Medium					
	High					
Rutting	Low					
	Medium					
	High					
Patching	Low					
	Medium					
	High					
Ravelling	Low					
	Medium					
	High					
Edge Failure	Low					
	Medium					
	High					

Date **Name** **Signature**