DEVELOPMENT OF NETWORK LEVEL PAVEMENT MANAGEMENT SYSTEM FOR LOW VOLUME RURAL ROADS

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Dissertation Submitted in Partial Fulfilment of the Requirements for the Degree of

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DECLARATION OF THE CANDIDATE & SUPERVISOR

I declare that this is my research proposal and this proposal does not incorporate without acknowledgment any material previously published submitted for a Degree or Diploma in any other university or institute of higher learning and to the best of my knowledge and belief it does not contain any material previously published or written by another person except where the acknowledgment is made in the text.

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R.M.K. Sandamal

I have read the proposal and it is in accordance with the approved university proposal outline. I am willing to supervise the research work of the above candidate in the proposed area.

Signature of the supervisor: …………………………. Date: ……………………………

Dr. H.R. Pasindu

DEDICATION

I dedicate this dissertation to Dr. H. R. Pasindu, my supervisor who encouraged me to conduct the study successfully, and to my parents, brother & wife who supported me throughout.

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ABSTRACT

In Sri Lanka, there is about 156,000 km length of roads and among those about 92% are considered as rural roads (LVRRs). These roads are playing a pivotal role in community development, transport of people, goods, and services in the rural areas by providing connectivity between residential, agricultural areas and the national road network. In the future, with rapid motorization takes place, it is expected the traffic volume on these roads will increase significantly. Limited funding, subjective and ad-hoc maintenance decision making has resulted in suboptimal maintenance level for these road networks. Moreover, the inability to collect extensive data which are needed to run most of the existing pavement management systems (PMSs) and the technical expertise required has resulted in the low usage of such systems by local road agencies. Therefore, there is a need to develop a cost-effective simplified approach for network-level decision-making to assist in pavement maintenance management.

The study explored the applicability of smartphone-based roughness data to assess the pavement condition of LVRRs as a novel pavement performance evaluating criteria by validating its accuracy compared with a Class III type roughness measurement equipment. The correlation value between the two measurements was high as 0.84. Even though, the relationship has shown that smartphone roughness slightly underestimates road roughness still it can apply to LVRRs as a cost-effective, accurate method. Moreover, it was assessed whether roughness results represent pavement distress conditions in the LVRRs. Regression models were developed to find the relationship between International Roughness Index (IRI) and key distress types. It was found that Raveling, Edge Breaking, Pothole, Edge Breaking, Edge Gap has shown a good correlation with IRI as 0.61, 0.56, 0.55, 0.52 respectively. Further, to evaluate the combined effect of distress on IRI progression, stepwise multiple regression analysis was conducted by considering the roadway width and the model for narrow roads had an R-squared of 0.89. For the wider roads the model accuracy is high as with R-squared of 0.86. Interestingly, pothole was identified as the key distress type in both models while edge breaking and edge gap only relevant in narrow roads. Finally, IRI progression was evaluated with the Pavement Condition Index (PCI) and a non-linear relationship was found with an R-squared of 0.75 from the sigmoidal function. Moreover, relationship between IRI with Pavement Serviceability Rating (PSR) was evaluated and found that a good relationship with R-squared of 0.76 for the model.

The relevant maintenance strategies used for LVRRs were identified by establishing threshold and trigger values based on the works of literature and current practice in the Sri Lankan context. To support the decision-making criteria, an analysis scheme was developed by using a defined decision tree. The objective function was established as the minimization of the average network IRI value which represents the maximum network condition. Two analysis systems were developed; one with Integer Programming and the other with a Genetic Algorithm (GA) based system. In addition to that, Engineer's judgment was compared with the two methods by using an illustrative example. From the results, it was found that GA is always provided the optimum work program while Integer Programming merged into a suboptimal level. Although Engineer's objective decision-making has shown significant variation when there is a budgetary constraint. However, when there is a sufficient amount of budget available most of the Engineer's judgments were also close to the optimum solution.

Further, in this study socio-economic importance was incorporated in the maintenance planning decision-making scheme by using the multi-objective optimization analysis. A socio-economic priority index was developed by using the priority factors namely traffic volume, land use, community importance & accessibility to the road network. In there, a network-level maintenance strategy budget estimation tool will also be introduced by considering different road surface conditions and maintenance strategies used in LVRRs. The set of optimal solutions for the multi-objective problem generated using the 'Pareto Optimality' concept. A case study was performed and found that the method would be useful in prioritizing the roads having socio-economic importance. Furthermore, another illustrative example was performed by incorporating safety performance in decision criteria using a predefined parameter called Cumulative Safety Index (CSI). The study has also shown that rather than spending money on optimizing a single objective, optimization of multiple objectives at a time would be a better option since the improvement of the existing network is higher in that case. Moreover, the multi-objective optimization approach would provide ability to include objective functions which cannot be incorporated in single objective optimization approach.

The core attributes of the proposed system are, reduced the data requirements, simplified the analytical tools and allowing users to customize considering the resource constraints in prioritization and optimization and that would allow road agencies to make objective decisions and optimize the road maintenance process. The finding from this research can be used for maintenance planning for local road authorities in Sri Lanka as well as for other developing countries by adopting the parameter defining for their local context.

Keywords: Roughness; low volume rural roads; pavement management systems; smartphone-based roughness data; socio-economic importance; multi-objective optimization

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LIST OF ABBRIVIATIONS

Abbreviation	Description
LVRR	Low Volume Rural Road
PMS	Pavement Management System
PCI	Pavement Condition Index
PSR	Pavement Serviceability Rating
GA	Genetic Algorithm
CSI	Cumulative Safety Index
HV	Heavy Vehicle
RDA	Road Development Authority
ADT	Average Daily Traffic
MOO	Multi-Objective Optimization
PRDA	Provincial Road Development Authority
HDM	Highway Development and Management Model
ADB	Asian Development Bank
UN	United Nation
FHWA	Federal Highway Administration
M&R	Maintenance & Rehabilitation
DM	Decision Maker
LCC	Life Cycle Cost
DoT	Department of Transportation
GIS	Geographical Information System
AASHTO	American Association of State Highway & Transportation Officials
AADT	Average Annual Daily Traffic
ESAL	Equivalent Standard Axle Load
USA	United States of America

ASTM	American Standard of Testing & Materials
AHP	Analytical Hierarchy Process
ANN	Artificial Neural Network
M-E	Mechanistic & Empirical
GPS	Geographical Positioning System
RMS	Root Mean of Square
CV	Coefficient of Variation
AC	Asphalt Concrete
HMA	Hot Mix Asphalt
PCC	Portland Cement Concrete
WSM	Weighted Sum Method
SOO	Single Objective Optimization
eIRI	Estimated International Roughness Index
cIRI	Calculated International Roughness Index
ANOVA	Analysis of Variance
VIF	Variation Inflation Factor
LKR	Sri Lankan Rupees
PI	Priority Index

1 INTRODUCTION

1.1 Introduction to the Road Network

The road sector is playing a pivotal role in the industrial and export development of a country with a direct and indirect relationship to the production sector. Therefore, it is essential to invest in road infrastructure development to improve the productivity of the economy. Moreover, the current demand for passenger travel in Sri Lanka is about 80 billion passenger kilometers per year, among that road transportation, which is contributing to 93% [1]. The increment of the total vehicles especially Heavy vehicles (HV) and low expansion of the road network, which is shown in Table 1-1, caused a significant deterioration in roads [2]. Therefore, road authorities must have focused on effective asset management in the road sector to reduce the pavement deterioration rate to provide a better functional condition to the users [3].

Table 1-1: Percentage Increase of Total Vehicles, Heavy Vehicles and Road Length to the Base Year 2013 [2]

Parameter	2013	2014	2015	2016	2017	2018
Total vehicles %	0	8.25	21.11	30.55	39.27	48.51
Heavy vehicle %	0	2.25	5.15	7.87	11.61	14.43
Total road length %	0	1.51	1.85	2.42	3.65	3.66

Sri Lanka has a large road network of about 12,496 kilometers of national highways (A, B & E class roads), and over 155,000 kilometers in the entire road network with a density of 2.38 km/km^2. However, more than 50% of roads are with gravel surface and 91% of total roads are considered rural roads [2]. In Sri Lanka, road administration is divided into three primary levels. National highways which include classes A, B and E (expressway) are managed by the RDA. Provincial Road Development Authority (PRDA) of relevant Provincial Councils has the responsibility to maintain class C and D roads. Local authorities such as municipal councils, urban councils, the Department of Irrigation, Department of Wild Life Conservation are managing rural unclassified roads. A brief description of the road management structure is shown in Table 1-2.

Table 1-2: Management Structure of the Road Network

Type and Class	Designated Function	Administration Authority
National Roads (Class A,B & E)	• Connecting major urban areas to the country's population and linking economic centers	Ministry of Highways and RDA
Provincial Roads (Class C&D)	• Feeder roads connecting settlements with markets • Provide access between national highways and consumer areas	PRDA of relevant Provincial Council
Local Roads (Unclassified Roads)	• Local roads providing access to specific locations • Linking agricultural and residential to the provincial and national road network	Municipal/Urban Council or other Local Authority

Increasing freight transport on these roads will deteriorate the pavement surface very quickly since 93% of the traveller kilometers are covered by road transportation. Therefore, an efficient transport system is essential for economic development because Sri Lanka is predominantly based on the agricultural production sector. In Sri Lanka, Road classification is based on principle functions, geometrical standards, road conditions, geographical region, and traffic level. Table 1-3 shows the distribution of road length, road density and pavement condition in recent past years for different road categories. That shows the major components of roads are rural roads with relatively higher density.

Table 1-3: Distribution of Road Length, Road Densities in Different Road Categories [2]

Item	Unit	2014	2015	2016	2017	2018	2019	2020[(a)]
Total Road Length	km	117,012	116,407	118,059	119,480	119,490	100,638	155,996
National Roads	km	12,369	12,380	12,380	12,380	12,390	12,438	12,496
Provincial Roads	km	19,083	18,397	18,353	18,900	18,900	N.A.	18,924
Rural Roads	km	85,560	85,630	87,326	88,200	88,200	88,200	143,500
Total Road Density	km/km^2	1.78	1.77	1.80	1.82	1.82	1.53	2.38
National Roads	km/km^2	0.19	0.19	0.19	0.19	0.19	0.19	0.19
Provincial Roads	km/km^2	0.29	0.28	0.28	0.29	0.29	N.A.	0.29
Rural Roads	km/km^2	1.30	1.31	1.33	1.34	1.34	1.34	2.19

N.A. – Not available, [(a)] - provisional

Provincial roads provide access between national highways and consumer areas, while local roads linking rural agricultural and residential to the provincial and national road networks. Constructing new roads concerning the demand could not be realistic due to the limited funding especially for local road agencies. Therefore, a significant effect should be put on the maintenance program to keep roads in acceptable functional condition. Moreover, to resist additional loading on the pavement, require reconstruction or rehabilitation strategies to perform by strengthening the existing performance. The distribution of existing road conditions of national roads is measured by IRI as a percentage is shown in Table 1-4 [2,4].

Table 1-4: Road Condition of National Roads as per IRI as a Percentage [2,4]

Category	**2013**	**2014**	**2015**	**2016**	**2017**	**2018**	**2019**	**2020[(a)]**
Excellent (IRI < 3 m/km) %	29	27	27	35	36	N.A.	39	42
Good (IRI 3 - 5.5 m/km) %	36	27	28	29	30	N.A.	26	27
Fair (IRI 5.5 - 7 m/km) %	8	9	9	10	13	N.A.	9	9
Poor (IRI 7 - 10 m/km) %	13	16	16	11	10	N.A.	10	9
Bad (IRI > 10 m/km) %	14	22	20	15	11	N.A.	16	14

N.A. – Not available, (a) - provisional

Provincial and local road funding availability is limited for improvement and maintenance works. Even though funding is limited, there is a large portion of class "C"," D" and unclassified roads which should be renovated immediately. Moreover, a significant number of unpaved roads have not been properly maintained and therefore are in poor condition while there is another considerable amount of gravel road that should be upgraded to paved.

The Central Government provides most of the budget requirements for the provincial and local council for regular and capital expenditures. Further, the Central Government negotiates with the Finance Committee to allocate domestic and foreign funds annually for road development by grants. Provincial and local councils apply for those grants by explaining their capital and regular expenditure through the National Finance Committee. There are several treasury funding sources are available for road development in the local authorities such as Government budget, local funds, foreign aid-related grants, foreign aid loans, various road user charges namely road tolls, vehicle license renewal fee, overloading fine, fuel levy etc.

There are several treasury funding sources are available for road development in the local authorities listed below [4].

- Government Budget
- Local funds
- Foreign aid related grants
- Foreign aid loans
- Different road user charges such as fuel levy, road tolls, vehicle license renewal fee, overloading fine etc.

Currently, in Sri Lanka, there is a gap between investment and savings, while for the major road infrastructure project and minor-sized projects, the country is relying more on foreign funds. The road sector has the highest influence by foreign financing and those projects are funded by multilateral and bilateral donors as listed in Table 1-5 [4].

Table 1-5: Foreign Financing Commitment [4]

<table>
<tr><th>Bilateral</th><th>Multilateral</th></tr>
<tr><td>China</td><td>Asian Development Bank (ADB)</td></tr>
<tr><td>France</td><td>World Bank</td></tr>
<tr><td>Germany</td><td rowspan="6">United Nation (UN) Agencies</td></tr>
<tr><td>Japan</td></tr>
<tr><td>Korea</td></tr>
<tr><td>Sweden</td></tr>
<tr><td>Spain</td></tr>
<tr><td>USA</td></tr>
</table>

As a developing country, to solve the serious issues of maintenance work of LVRRs, it is essential to establish a system to provide accurate and reliable resource allocation which ensures that the funds are utilized properly. It is needed an efficient asset management system for pavement Maintenance and Rehabilitation (M&R) works due to the scarcity of available resources. This chapter describes the works of literature on pavement maintenance management, effective road condition evaluation, prioritization and optimization tools used in current practice, the framework of the decision-making process etc.

The selection of a timely maintenance strategy is an important aspect of maintaining the pavement cost-effectively. The use of the correct maintenance strategy at the right time on the right road segment will help to maximize the benefit. This depends on the pavement condition, the life cycle of the road and constraints. When the road surface is in relatively good condition applying preservation maintenance cost is much lower than waiting until the condition has been worse to apply rehabilitation strategy. Especially, in the provincial and local road networks, managing road assets is a complex task due to the abovementioned constraints. Therefore, a systematic process is needed in planning the maintenance program of such a road network while concerning resource constraints prevailing in the local authority. Therefore, a Pavement Management System (PMS) should be established at the local agency level.

Conventional PMSs are data-intensive and require a significant level of technical expertise to collect, analyze the data [5]. The collection of several types of data relating to pavement conditions such as distresses is time-consuming and costly, especially conducting at a network level. The core attributes of a system to be used in local agencies should be included with reduced data requirements, simplified the analytical tools and allowing the user to customize concerning the resource constraints. Several factors such as pavement structural and functional condition, social-economic importance, traffic volume, etc should be considered prior to implementing the analysis stage.

PMSs have been developed worldwide by incorporating both prioritization and optimization models into pavement maintenance. However, most PMSs do not fully incorporate those approaches into the analysis, there is limited success for authorities by only achieving a suboptimal solution for the maintenance planning. Therefore, in pavement maintenance management, it is essential to incorporate both optimization and prioritization techniques to achieve the best maintenance strategy.

Pavement maintenance optimization approaches include mathematical models or algorithms that find the combination of ideal maintenance strategies on the road network which optimize the defined objective function(s). Total cost for a financial year, overall network condition, overall safety performance and pavement structural performance are the parameters frequently used in pavement maintenance optimization. The decision tree is prioritizing the key road links in the network with the help of suitable generic constraints underlying the threshold defined based on the road agency's requirement. Network-level optimization includes maximizing or minimizing an objective function of using binary, integer or real-valued decision variables while satisfying equality and inequality constraints [6].

The optimization in PMS determined optimal solution set using single-objective optimization due to it can be easily solved by linear programming and non-linear programming incorporating mathematical models. In this study, the primary analysis is the maximization of network conditions under budgetary constraints. With the increase of economic and social importance in maintenance planning, there is a need of quantifying multiple objectives in PMSs. Therefore, the decision-making process must be addressed to solve multiple objectives at a time using optimization techniques such as linear programming, optimal control theory and heuristic non-linear programming, etc [7].

An ideal maintenance planning system maintains all the road links in acceptable condition while requiring a reasonable budget while utilizing resources. Even though there are several systems developed worldwide for Pavement Maintenance Optimization and Prioritization, there is no proper system for Sri Lankan local road agencies to follow. Therefore, it is needed to develop such a system with the capability of utilizing the resources while achieving a global optimal solution for maintenance planning.

1.2 Problem Statement

Existing PMSs have several limitations as discussed in earlier section that makes them less suited to be implemented for local road networks in Sri Lanka. Therefore, the proposed PMS should consider the limitations and constraints prevalent in local agencies. The functioning of the PMS should only require data that can be acquired with minimal financial and technical resources, analysis tools should be comprehendible at a technical officer's level, yet give consistent and objective results, and the system should be customized to incorporate socio-economic factors. Further, it should have the ability to handle multiple objective functions to be an effective system.

1.3 Research Objectives

The objectives of the research are as mentioned below,

- Identify a suitable performance indicator which can sufficiently reflect the pavement distress condition.
- Identify a cost-effective method to collect the required data to assess the pavement condition for that indicator.
- Develop an analytical approach using network level optimization, decision tree to eliminate the limitations of subjective maintenance decision making.

1.4 Scope of the Research

In this research, LVRRs are defined as the roads in which the ADT <3000 veh/day and that are not categorized under national roads according to the road classification of Sri Lanka. Given that the existing usage of PMS for LVRRs in Sri Lanka is minimal. There is no proper system to followed for local authorities because the available PMS focus more on database development, condition evaluation and lack the analytical module that can be used to assess maintenance strategies. Therefore, the requirement for a new PMS framework is essential to manage the LVRR network.

This study focuses on developing a suitable pavement condition evaluation criterion by identifying the minimum data required for the database. Moreover, it is structured as a decision tree based on the selective data inventories by defining relevant thresholds for maintenance strategies.

Through this research, developing the analysis tools to utilize fund allocation, a single financial year analysis process is developed with the objective function of maximizing the overall network condition. Moreover, a method to find the optimum work program for the maintenance work is established in the single-objective optimization approach. Further, the multi-objective decision-making process is established to incorporate different objective functions which cannot be accommodated in single-objective optimization.

The research scope is defined by incoperating following aspects;

- Identify the road inventory types and establish a suitable performance indicator which can reflect the pavement distress condition for maintenance planning in-network level.
- Identify a cost-effective method to collect the required data to assess the pavement condition for that indicator.
- Identify the maintenance strategies and respective thresholds for low volume rural roads which can be used in the decision tree to support the decision-making process. However, these thresholds must be incorporated in a user-customizable way that based on the road agency maintenance policies and optimization level those shall be changed.
- Develop an analytical framework for optimize network level pavement condition, incoperating the decision tree to eliminate the limitations of subjective maintenance decision making,
- Also, to incorporate objective functions which cannot be accommodated in single-objective optimization analysis, a multi-objective optimization analysis scheme is to develop which can find the optimum work program for a given network.

1.5 Outcomes of the Research

Following outcomes were generated from the dissertation:

- The road inventory types that are required in the pavement management database.
- International Roughness Index (IRI) and pothole counting are selected as the condition evaluation parameters and smartphone-based roughness measurement is used as the cost-effective data collection methodology.
- Maintenance strategies and respective thresholds for LVRRs are identified and a decision tree is developed to support the decision-making process.
- Developed analysis tools to prioritize roads based on the socio-economic importance, to utilize the fund allocation and to optimize the objective functions primarily to maximize the network condition.
- Adopted MOO approach into the decision-making process.

1.6 Arrangement of Dissertation

The structure of the dissertation is as follows;

Chapter one describes the background of the research by demonstrating the road network and administration scheme in Sri Lanka. Moreover, that included the scope of the study, objectives and research outcomes.

Chapter two is the literature review of the study. Sri Lankan road network and management structure were evaluated to get an idea of the relevant stakeholders. Moreover, the various components in a PMS were assessed and a comprehensive review of pavement condition evaluation techniques, project prioritization methods and optimization approaches have been made. In addition to that, various PMS developed worldwide were assessed by highlighting their special characteristics. Further, pavement roughness measurement techniques were analyzed by paying special attention to smartphone-based roughness measurement. Finally, by evaluating current practices in Sri Lanka, the relevant threshold values, maintenance decision criteria and parameters were identified which were used in the system development in chapter 4 and 5.

Chapter three is proposed smartphone-based roughness measurement as the pavement condition evaluation parameter alongside the pothole counting. The data collection procedure is described in this chapter mainly roughness, distress and inventory data types. Moreover, smartphone roughness was compared with a conventional method and evaluated the capability of IRI to capture the distress prevailing in LVRRs. Finally, in this chapter suitability of IRI was investigated instead of PCI and PSR Indices which needs extensive distress data to calculate.

Chapter four describes the development of the decision-making tools in the proposed framework. Two main approaches namely Integer Programming and GA base approach were conducted to find the optimal work program for a LVRR network. This is consistent with the Single objective function to optimized namely average network IRI value. Moreover, a decision tree was developed by including generic constraints. Two case studies were illustrated in such a way one compared Integer Programming vs GA and the other one compared Integer Programming, GA with the Engineer’s objective judgment.

Chapter five discusses the MOO approach in the decision-making of maintenance work programs. Subsection 5.1 explains the use of socio-economic importance as the secondary objective in the MOO approach. The feasible solutions were generated using the GA-based framework and with the use of the Pareto optimal concept the Pareto front was identified. Two optimal solution selecting methods were used namely the Utopian method and weighted sum approach. A case study was conducted to illustrated the proposed method. Moreover, another case study was conducted by establishing safety performance as the secondary objective. The relevant Pareto fronts and optimal solutions were generated for the case study.

Chapter six concludes the dissertation with a summary of the research findings and recommendations for further studies in the research area.

2 LITERATURE REVIEW

2.1 Pavement Management Systems

A PMS is defined by the Federal Highway Administration (FHWA) as “a systematic process that provides, analyses, and summarizes pavement information for use in selecting and implementing cost-effective pavement construction, rehabilitation, and maintenance programs” [8]. The primary objective of a PMS is to optimize the economic benefits by minimizing the sum of maintenance costs and road user costs. PMS provides a consistent, objective and systematic system to determine priorities and management schedules while allocating resources for M&R works [9].

The road network is consisting of many kilometers of roads, a simple decision-making process by incorporating the Engineer’s experience is not adequate. Therefore, it is needed more structured, extensive framework to enhance the performance of the road network in a pre-planned manner. Especially for most of the local authorities, their road network is considered as the most valuable asset under their control, therefore is needed a system to maintain it in the optimal state [10]. Highway agencies maintain, operate and improve their resources under several challenges that include:

- Budgetary constraint due to diverted to support and other services
- Limited resources and lack of staff and skill level
- Large road networks with a significant amount of backlog of M&R requirement
- Increased the accountability to the funding providers
- Increasing public expectations

Pavement management decision criteria incorporate three levels such as strategic level, network level and project level. At the strategic level, the Decision Maker (DM) decides on choices that affect long-term effort and these decisions included setting performance goals, budget allocation and maintenance strategies. Network-level pavement management is involved with formulating pavement preservation policies, prioritization of roads and estimating the budget needed for M&R works. Furthermore, information about the current and future network conditions is used to make decisions about the effects of various short and long-range budgets. The project-level decision criterion is the selection of site-specific for individual projects or tasks. The critical difference between project level and network-level optimization is that the resulting selected option at network level consideration is not necessary to be the optimal one when considering at the project level [10].

The use of an effective PMS by a road agency is provided a significant amount of benefits as a state by Washington State Department of Transportation (WSDOT) [11]:

- Providing a centralized location for store pavement inventory data, pavement condition information, M&R records, etc.
- Providing an analysis tool to evaluate the consequences of the variation of funding levels.
- Improve the maintenance scheduling hence resulted in the reduction of excess rehabilitation cost.
- Providing the information to analyze the cost-effectiveness of various maintenance strategies.
- Allowing the road agency to answer "what-if" type questions regarding pavement management and budgetary scenarios.
- Justifying budget needs to officials and other stakeholders.

The efficient planning and management of road networks depend on the development of a systematic pavement management process. Figure 2-1 illustrated that the steps must be performed to fulfil the road agency's needs in customizing the pavement management process [12]. The described steps are mainly categorized into the three main sections as data, analysis and feedback. The data section included the road inventory, pavement M&R and condition history, pavement condition survey data, traffic and the database. The analysis is comprising of condition, pavement performance and investment analysis. Moreover, in the feedback section, evaluation and updating of procedures by calibrating the relationships using PMS are performed. The use of the abovementioned process and optimize the approach will be provided accurate and effective management of road networks using a PMS.

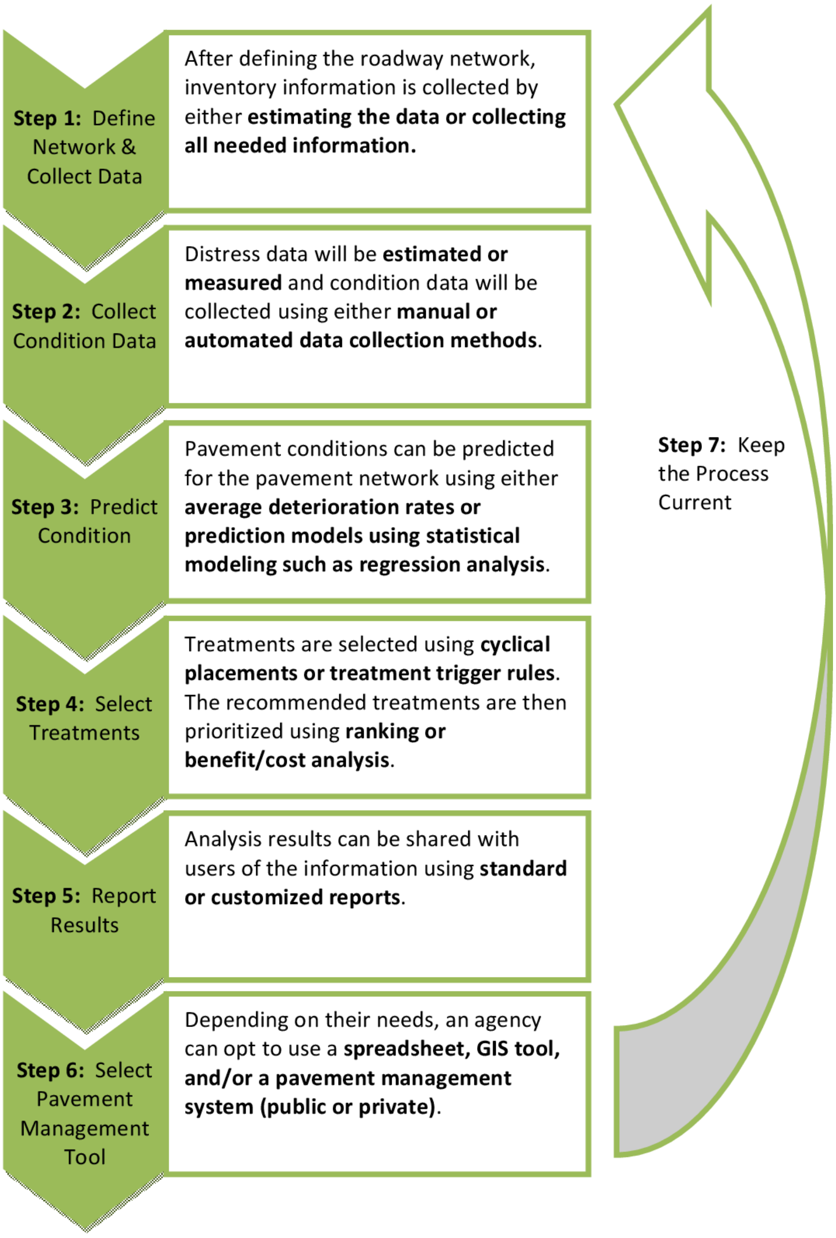

Figure 2-1: Pavement Management System Process [12]

2.1.1 Components of a Pavement Management System

The effective PMS provides objective, systematic and consistent procedures to determine resource allocation, identified priorities for pavement M&R works [9]. The main target of most PMS is the maximization of the performance of pavement M&R works by utilizing available funds. In general, the PMS process consists of several components: Network inventory, condition survey program, pavement performance prediction modeling, and planning and evaluation method [13]. Network inventory data included planning and identification data, geometry data, design and construction data, pavement material data and other structural data. Among the components described above, the pavement condition evaluation program can be identified as the most important component. Those are used to collect, store and analyze the road condition regularly. Distress surveys, roughness measurements, friction measurements are the basic data types used. Moreover, a database is used in sorting and storing the collected data in the condition evaluation program. Further, analysis tools are incorporated to decide repair strategies and suggest cost-effective projects to implement. In this analysis scheme Life Cycle Cost (LCC) analysis optimization algorithms, road prioritization methods, condition prediction models are used as analysis tools.

The planning module component of the PMS is used to decide what maintenance activities should be taken. To maintain or improve the condition of the pavement, the Engineer would be able to establish a maintenance program to be implemented in the future planning period.

A typical PMS process including the key components is shown in Figure 2-2.

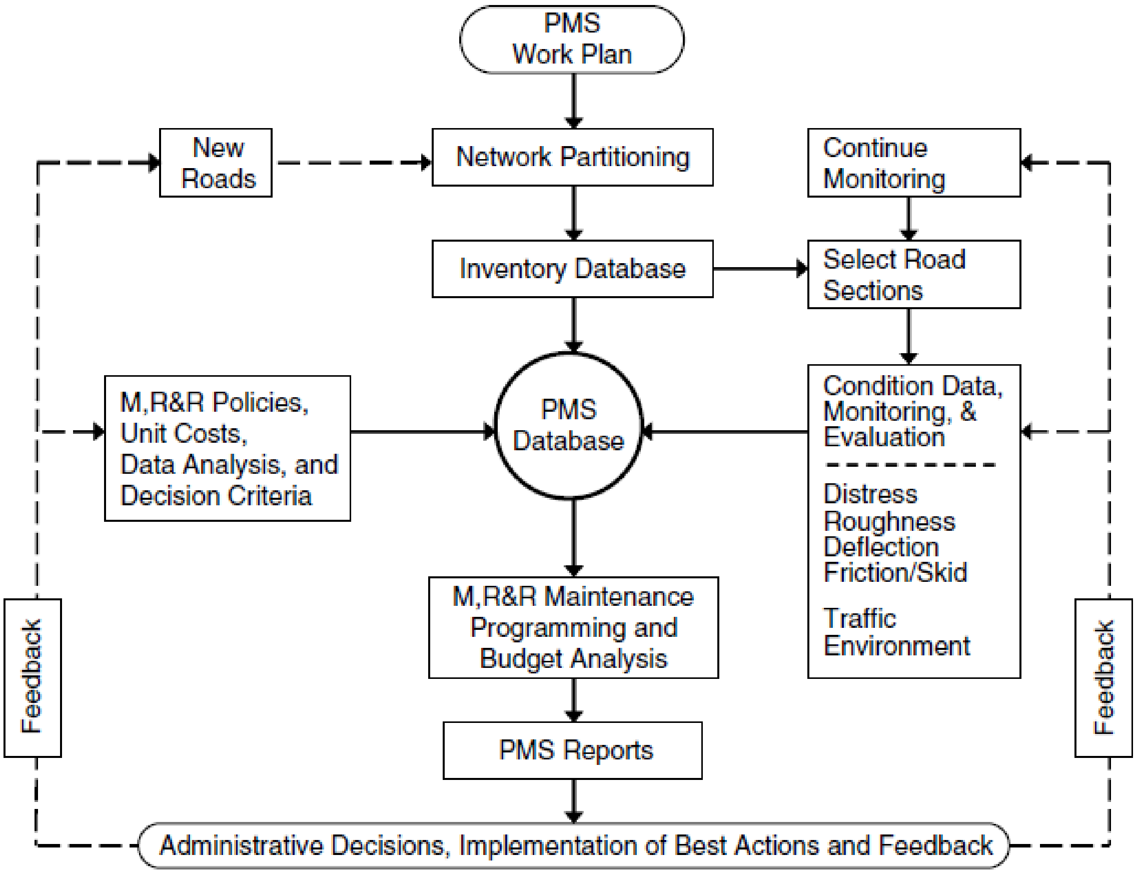

Figure 2-2: A Typical PMS Process [12]

2.1.2 Best Practices in Pavement Management

The effective planning and management of a road network depend on the development of a systematic and repeatable management process to fulfil the road agency's needs in customizing the pavement management process [12]. There are several constraints to be faced for road agencies when developing a PMS and by incorporating best practices crucial issues can be overcome. Further, those practices can be implemented to the integrated parts of PMS such as institutional framework, road sector financing and budget allocation process, etc. ADB Introduced the best practices in road asset management as described in Table 2-1 [4].

Table 2-1: Best Practices for Developing Countries [4]

No.	Best Practice	Description
1	Limit the data to be collected	This focused on limiting the data collection with the minimum use of time and money and to be collected minimum data required to be implemented. Moreover, it should be done with a significant amount of accuracy, implementing reliable methods by ensuring the data quality
2	Make the database easy to use	The database should be properly structured and the use of local language makes it easily accessible to the different levels of DM. Moreover, it can be used to monitor the road sector's performance.
3	Start with a simple software	The system should be simple, inexpensive and user customize at the start. With time it can be developed based on the responses of the road management.
4	Institutionalize from the start	The system should be institutionalized from the start by identifying responsibilities and resources for the operation
5	Publish annual performance	Publish an annual performance which would help road network to be monitored and provide an incentive for the data collection
6	Integrate into the decision-making processes	Use as a planning tool rather than as a monitoring tool and also needs to be integrated into the decision-making process.

PMS with effective data management will result in stable, high-quality information and more reliable understood data. Further, this will provide financial benefits and quantifiable improvements in service delivery. These meaningful data can form the basis for sound decision-making while reducing data duplication and redundancy which leads to cost-saving [14]. Furthermore, European Road Administrations describes [14], the 7-steps to successful data management in PMS as follows;

1. Determine business information needs
2. Review of the current situation
3. Data analysis
4. Design a data management regime
5. Develop an implementation plan
6. Establish a data management regime
7. Ongoing review and improvement

2.1.3 Pavement Management Systems Developed in Worldwide

In the late 1960s, the road agencies shifted from the design and build process to repair and maintenance mode due to the need to preserve significant investment on the pavement with the rapid increase of heavy truck traffic and aging. At the same time, budgetary limitations were arising and that situation creates a backlog of M&R needs in the road network [15]. The maintenance engineers have come up with an idea of a systematic process which able to provide cost-effective solutions to limited resources, hence created the concept of 'PMS'. The first project-level PMS is developed by the Washington State DoT in 1974 with models and timing recommendations for various M&R actions [16]. The early systems are simple and based on the ranked projects using the factors such as pavement condition and traffic. Moreover, these are not included future performance prediction or economic analysis hence one-year program was developed. Later, in the early 1980s, network-level management is incorporated and the Arizona DoT is developed as a PMS with a network perspective [15]. Later, road agencies have developed more sophisticated systems using computerized processes. The systems are consisting of several functions such as data collection and data management, pavement performance prediction, economic analysis, project prioritization, optimization, institutional issues, and information technology [15]. There are several PMS are developed in different countries described here.

2.1.3.1 Portugal PMS

Ferreira et al. (2009) [17] presented a geographical-information-system (GIS) based PMS for Oliveira do Hospital to local road agencies to use in their decision-making process. The system included a network database, cost model, pavement performance model incoperating present serviceability index (PSI), pavement quality evaluation tool and a decision aid tool. The ultimate goal of the system is the minimization of the total expected total costs over the life span while keeping pavements within the accepted quality standard level.

The database is comprising of road classification, traffic data, climate data, pavement history, M&R strategies, etc. Moreover, the quality index is calculated by using a modified version of the American Association of State Highways and Transportation Officials (AASHTO) PSI equation which includes roughness, rutting, surface disintegration, rutting and patching. The decision aid tools have been developed using a computer program called GENEPAV-D, which uses a heuristic based on a genetic algorithm (GA) in the optimization process. This is a project-level optimization system that determines the optimum M&R strategies to be applied to each road section annually and the components of decision aid tools are shown in Figure 2-3. These M&R works are defining as 9 different actions and strategies are categorized into 5 components as do nothing, non-structural maintenance, minor rehabilitation, medium rehabilitation and major rehabilitation. Further, the decision aid tool is a single-objective optimization model by incorporating 9 equal and unequal constraints such as warning level, annual operation, agency cost, user cost, annual budget, etc. Moreover, The PMS is used generally annually or biannually to get revised optimum M&R program.

The PMS is flexible to incorporate any of the suitable pavement condition indicators which can be used as an alternative depending on the data availability. Moreover, since this is an open system some modifications can be added based on the need of the municipal road engineers.

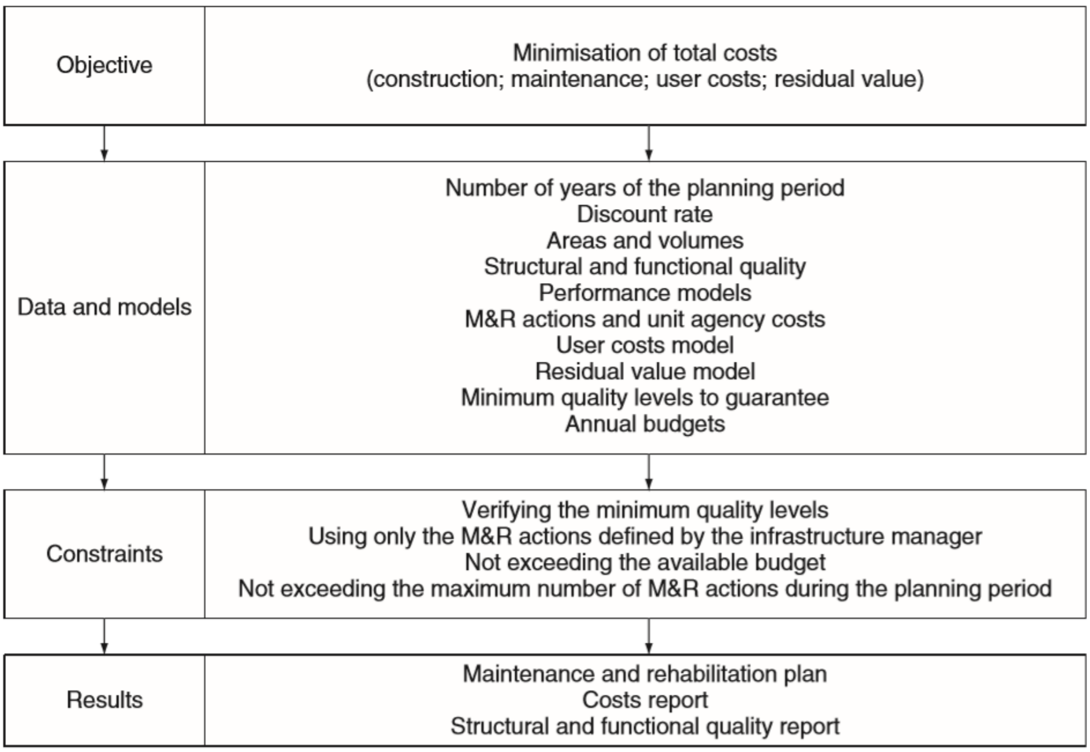

Figure 2-3: Decision-Aid Tool Components of Portugal PMS [16]

2.3.1.2 Singapore PMS

A computer program name 'PAVENET' formulated using the GA to make the analytical decision in pavement maintenance management, is introduced by Chan et al. (1994) [18] at the National University of Singapore. The PAVENET is a multi-year Single Objective Optimization (SOO) system that maximizes the work produced in total workday units and is known as the first successful use of GA in the PMS optimization process. In the multi-year analysis, two planning periods are defined as active and passive. The active planning period is defined as the time duration only corrective repairs are allocated the resources while the passive planning period considers only corrective works. Moreover, the annual budget and resources are used as the constraints under a fixed interest rate. Furthermore, the penalty method is used here to prevent discarding the infeasible solutions when problem parameters are highly constrained. Cracking, rutting and surface disintegration are used in the condition evaluation function while traffic condition is incorporating in the deterioration modeling. The optimization stopping criteria is in two forms which can be chosen by the user either when a single genotype is reached, or a specified number of iterations reached. The use of GA has the capability of obtaining optimal or near-optimal solutions by changing the initial population, mutation rate, convergence criteria, etc. Later, Fwa et al. (2000) [19] is further developed the PAVENET system by incorporating the MOO technique using the Pareto optimal concept. However, the tools included in the previous version such as the rank-based priority model, priority weighting criteria are employed in the improved version also. In this improved version in addition to the maximized work production, minimization of total maintenance cost and maximization of the overall pavement condition are used as the objective functions.

2.1.3.3 Australian PMS

In Australia, interest in procedure to PMS was initiated in the middle 1970s [20] while developing road condition inspections which is identified as the primary need for performance evaluation. RTA PMS software is implemented as a result of these studies, and which was the forefront of road assets management in Australia [21]. The system consists of several modules such as a road location system, ROCONDSO inspection system, road register local, CMISPRO graphical information system, TNOS site-specific treatment optimization, FNOS strategic budgetary planning and LCC program [22]. The condition database includes 5 distress types including roughness and based on those 8 treatments are defined in the site-specific treatment optimization. Further, the optimization process is developed by using integer programming as a software package called TNOS. For the given budget constraints, TNOS has selected the pavement or surface treatments at particular road segments.

The system included a strategic budgetary planning PC- based software called FNOS which allows the council to select various road condition targets while computing the budget requirement using Markovian probabilistic models. The LCC program of the system is allowed the user to further analyze the project-specific outputs obtained from the PMS. This module computes the net present worth and equivalent annualized cost at 6 different interest rates which provide access to local road authority to further optimization of the life cycle planning at a project level.

2.1.3.4 Japan PMS

MLIT-PMS is a road asset management system with pavement databank, short term project-level planning system and long term network-level planning system which is developed by the Ministry of land, infrastructure and transport of Japan [23]. The short-term planning system provides access to get decisions in repair locations, relevant work strategies by using the pavement databank [23]. Moreover, it included a repair prioritization sub-system which determines repair strategy priority for each road section. Further, this system determines the priority classify roads in terms of PINDEX which has a score of 1 to 3 and is derived from the maintenance control index (MCI). MCI is a function of roughness, cracking ratio (%) and rut depth which has an upper bound of 10 [24]. PINDEX score 1 indicated that the road needs immediate repair while 2 indicate a repair is desirable to improve the lifetime performance and a score of 3 refers that no need for repair.

MLIT-PMS is using the ‘worst first’ prioritization technique in short-term project-level planning and linear programming optimization in the long-term network-level optimization process. As mentioned earlier in this chapter, the use of worst first or linear programming only provided a sub-optimal solution in the optimization process therefore, the system is lacking with tie-breaking capability when compared with other alternative solutions with equal strength.

2.1.3.5 Mississippi PMS

Mississippi DoT has been used a computerized PMS since 1986 in their road network management while having a comprehensive construction history database, pavement condition data and the assets inventory evaluation system [25]. In 1989, a state-wide PMS is launched using the product developed in the pilot program by Mississippi DoT. In there, a basic data collection procedure is included roughness and distress data collection which is implemented in the PMS. In the pavement condition evaluation process, IRI is converted to a pavement roughness rating with a lower bound of 0 and an upper bound of 100. Moreover, the distress condition is measured by the distress rating in an index of Pavement condition rating (PCR) which is ranged from 0-100.

Further, in the prioritization approach for selecting roads to immediate repairing the 'Worst first' method is used while roads having PCR< 72 or rut depth > 0.25inch is considered as the priority category. However, worst first technology only provides a sub-optimal solution in the decision-making process, later introduced new PMS software tools by focusing to achieve assets management requirements Ensuring the quality of pavement management data by Preserving institutional pavement management knowledge [25].

2.1.3.6 Sri Lankan Road Assets Management System (SLRAMS)

In 2015, RDA Sri Lanka has developed the Sri Lankan Road Assets Management System (SLRAMS) which is a web-based integrated Road Asset Management System by upgrading the existing Asset Information Management System (AIMS) system. In this system, the data collection process consists of detailed inventory data and traffic data collection which are used as the input to the system. Roughness, geometry data and detailed distress data are implemented in the decision-making system. There are 12 modules included in the system such as Road information system (RIS), Pavement management system (PMS), Routine maintenance management system (RMMS), Traffic information system (TIS), Crash information management system (CIMS), etc. Moreover, the analysis and decision-making criteria are supported by HDM-4 software. The project prioritization is based on the economic indicator of the ratio of Net Present Value to the Financial Capital Cost which is analyzed by the HDM-4. Further, the financial model was developed using RONET software and the analysis can be performed either in single-year or multi-year analysis. Furthermore, the M&R planning is conducted as a 10-year plan which includes development, maintenance and improvement of the road network by using the prioritized roads employing Life Cycle Cost Analysis of HDM-4.

The summary of the developed PMS is described in Table 2-2.

Table 2-2: Summary of the Developed Pavement Management Systems Worldwide

Country/ Region	**PMS Type**	**Condition Evaluation Method**	**Components of the PMS**
Portugal [17]	Project level single objective system	• Geographical-Information-System (GIS) based system which collects Roughness, distress, traffic data, climate data	• Network database, cost model, pavement performance model based on present serviceability index (PSI), quality evaluation tool and a decision aid tool • Heuristic-based on genetic-algorithm (GA) is used in the single-objective optimization process
Singapore [18] (PAVENET)	Multi-year multi-objective system	• Cracking, rutting, and surface disintegration are used to condition evaluation • Traffic data used for deterioration modeling	• GA used to make an analytical decision • Rank-based priority model, priority weighting criteria are employed
Australia [19] (RTA PMS)	Network-level and project level single objective system	• 5 distress types including roughness GPS based system to data collection	• Road location system, ROCONDSO inspection system, road register local, CMISPRO graphical information system, TNOS site-specific treatment optimization, FNOS strategic budgetary planning and life cycle costing (LCC) program • The optimization process is developed by using integer programming • Budget requirement predicted by using Markovian probabilistic models

Japan [20] (MLIT-PMS)	Short term project level system and long-term network level system	• Roughness, cracking ratio (%) and rut depth	• 'Worst first' prioritization technique in short term project-level planning • Linear programming optimization in long term network-level optimization • Pavement databank
Mississippi [21]	Single objective network level	• Roughness and distress data	• Construction history database, pavement condition data and assets inventory evaluation system • 'Worst first' prioritization technique
Sri Lankan Road Assets Management System (SLRAMS)[26]	Single objective optimization system for single or multi-year	• Roughness, distress data & geometry data	• 12 different modules included such as Road information system, PMS, Traffic information system, Crash information management system, etc • Data base developed using GIS • Budget optimization is used as the objective function

Even though there are already developed various PMSs in worldwide still those systems difficult to adopted to the Sri Lankan context due to several reasons. SLRAMS system is developed by the RDA, Sri Lanka also difficult to use in LVVRs. The SLRAMS consists of 10 different modules and pavement management system is only one component in the asset management system (Figure 2-4) [26]. To run this system extensive data is needed to the Road Information System (RIS) such as Road network, Road Link, administrative boundaries, detail distress data (type & extend), roughness, FWD deflection data, pavement history, project completion, etc.

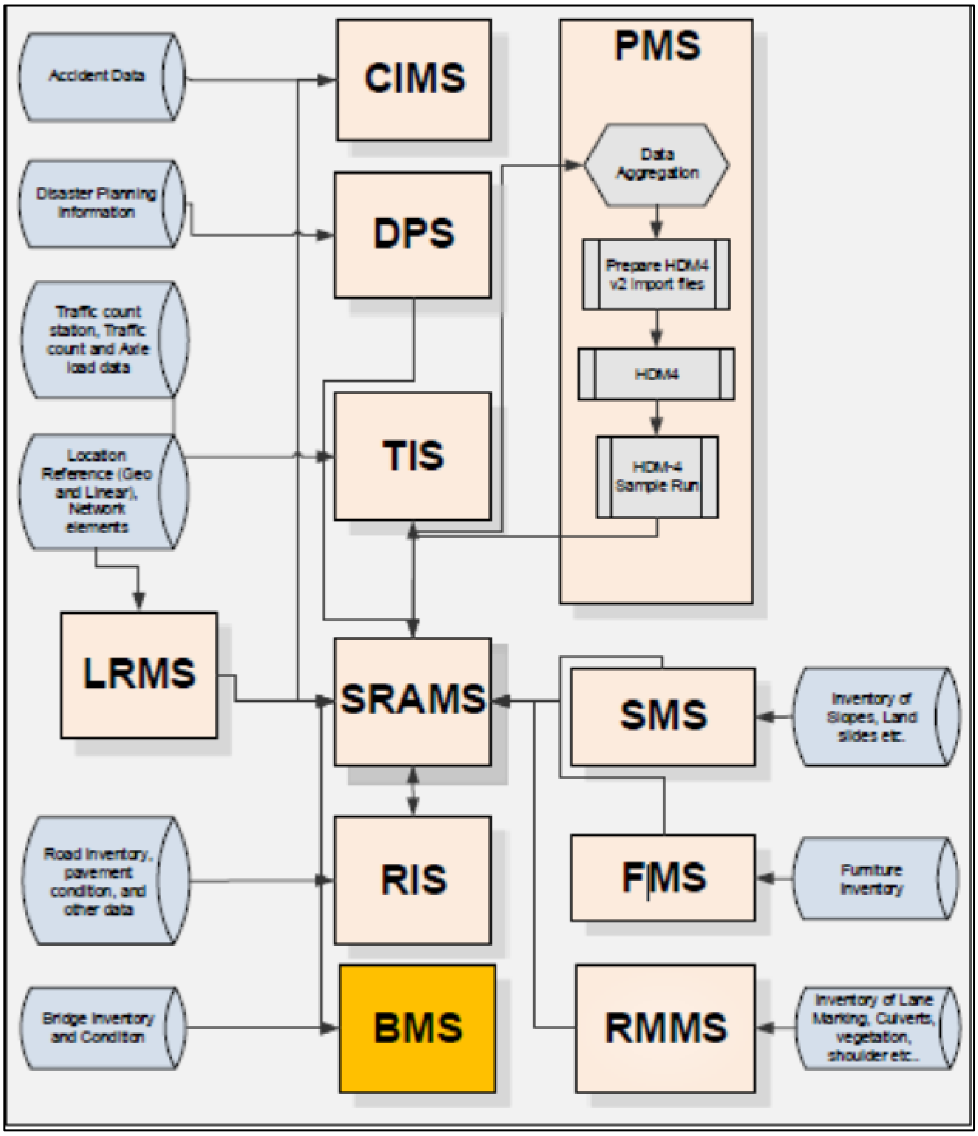

Figure 2-4: Framework of the SLRAMS system [26]

This extensive data collection is difficult for local road agencies due to a lack of technical knowledge, human resources & budget constraints. Even though a large amount of data has been already collected as input to the RIS module in SLRAMS, it is difficult to monitor the pavement condition on regular basis. With the pavement deterioration, extensive data collection on regular basis even on the roads which are already collected is difficult. Therefore, updating/monitoring the pavement condition data and inventories are difficult for local road agencies. Hence, a PMS with cost-effective & reliable data collection techniques is needed for local road agencies, the data inputs in SLRAMS are difficult to handle for them and even monitoring on regular basis also difficult. Also, SLRAMS analysis is done by the HDM-4 software by using input files. Due to the lack of technical experts, it is difficult to use in local authorities.

2.2 Definition of Low Volume Roads

The definition of LVRRs differs from country to country based on the traffic characteristic, road administration type, etc. There is no single approach to defining LVRRs. There are different volume thresholds published, particularly to set design guidelines. Some states have adopted definitions of LVRRs to define the scope of special funding programs. LVRRs in rural areas provide access to local business, healthcare and education and those transport links are named lifeline roads because they are vital arterials to that community [22]. Two main parameters have been used to define the LVRRs; traffic volume (either in terms of ADT or AADT), design traffic load (ESAL) and total HV in design life. Most of the LVRRs around the world consist of a single-lane gravel road or native surfaces to a particular country. Moreover, even in developed urban areas, the road links which are located at the end of the transportation network can be treated as LVRRs due to their low conventional design standards. FWHA shown that low volume roads vary from 400 to 1000 veh/day hence found that most of the rural roads would fall into that category [25]. In brief, Table 2-3 is illustrated the defined threshold values by different researchers worldwide.

Table 2-3: Threshold Value for Low Volume Road Definition in Worldwide

Country/Region	Low volume road threshold value
Sweden [22]	ADT value less than 360veh/day
Zimbabwe [23]	Road having equivalent standard axle load (ESAL) < 0.3 million in 20-year design life
Minnesota Department of Transportation (MnDoT) [24]	Road having equivalent standard axle load (ESAL) < 1 million in 20-year design life (AADT < 2300veh/day)
Pennsylvania [25]	ADT < 500 veh/day
	ADT < 5,000 veh/day and 20-year ESAL < 3 million
FHWA [25]	Annual Average Daily Traffic (AADT) < 1,000veh/day
Spain [25]	ADT < 450veh/day
Nordic [25]	ADT< 1000veh/day
Idaho DoT [25]	Commercial vehicle AADT < 300 per day
Navada DoT [25]	AADT < 400veh/day
USA [27]	ADT< 2000veh/day
Saskatchewan [28]	AADT < 1200 veh/day

In the Sri Lankan context, RDA was defined LVRRs as roads whose annual daily traffic (ADT) lesser than 5000 veh/day [1]. Moreover, different researchers have established different ADT values as the threshold for their studies. Piyasena (2012) [29] and Gamage et al. (2016) has established a threshold for LVRR terminology as 1000 veh/day [30]. Since in developing countries vehicle composition is dominated by three-wheelers and motorcycles which has passenger car unit (pcu) values around 0.3, 0.5 respectively. That gives the equivalent pcu/day compared to other countries, that uses 1500 - 2000 veh/day which is then closer to 3000 veh/day used in developing countries.

2.3 Pavement Condition Evaluation Techniques for LVRRs

Pavement condition evaluation typically consists of four aspects, i.e. distress condition, evaluation, pavement roughness measurement, skid resistance and structural capacity evaluation [31].

Pavement-related distresses are the data type that is primarily used as a basis to decide the maintenance requirement on a particular road stretch. The distress data is collected usually in form of visual observations (Windshield surveys) or through images or videos [32]. In addition to that, automatic data collection equipment is collecting distress data accurately nowadays [33]. Pavement distress is provided signs of pavement deterioration which manifests into three categories as surface disintegration (raveling, pothole, polishing), cracking (longitudinal cracks, transverse cracks, alligator cracks, block cracks) and surface deformation (rutting, distortion) [34].

Raveling, pothole, fatigue and longitudinal cracking, edge break and rutting are the types of distresses that are commonly observed in rural road networks according to a study on rural roads by Mane et. al. (2016) [35], these were used to develop guidelines for distress rating system. Quantitative methods are still useful for assessing and rating road conditions based on defined severity levels and extents. Among those Potholes were found as the most common defect type which is used in the assessment as a study performed by Kirbas and Karasahin (2017), Mittal et al. (2017) [36, 37]. It was found that, regardless of whether the defects are in vehicle or pedestrian routes, the common ones are the same.

As illustrated by Nkomo et. al. (2016), if the selected distresses had both depth and width less than 15 cm, the severity was classified between 0-4 and if any measurement was more than

15 cm then it was given the rating of 5. An extent is defined by percentage area classified as A-E with extent less than 5% is considered as A and greater than 80% as E. Based on the value of extent*severity, the treatment is applied on pavement surface by addressing distresses such as pothole, rutting and loose materials [35].

A quick and simple rural road condition measurement method of hierarchical structure is developed by Beckemeyer (1995), which also includes traffic safety and drainage condition into the existing pavement condition evaluation methods [38].

Surface condition evaluation of rural roads in Patna, Bihar [39], a video graphic survey was carried out of 37 km roads by fixing a camera on a bike that moving at 20 kmph constant speed. Distresses such as block cracking, raveling, patching were captured through the rectangular shape of the camera setup while circle and ellipse measurements were used for pothole counting. Linear measurements of longitudinal cracking, edge cracking were measured with linear setup. The study proposed a cost-effective method by combining video graphics and image processing which capture the most common distresses of pothole, raveling, cracking accurately.

Pavement roughness evaluation is referred to ride quality measures primarily by IRI, profile data and Present Serviceability Rating (PSR) data. Pavement roughness indicates the user comfortability along the particular road segment.

Pavement roughness can be measured by using various indices such as Ride Number (RN), International Roughness Index (IRI), Half-car Roughness Index (HRI), Mays Ride Meter (MRM), Quarter-car Index (QI), and Present Serviceability Index (PSI). Among those, IRI is globally accepted as a suitable parameter to measure pavement roughness. The IRI reported in unit m/km was developed by the International Road Roughness Experiment held in Brazil in 1982 and adopted as the unit to define roughness.

The IRI summarises the roughness qualities that impact vehicle speed, operating cost while providing user comfort indication. Figure 2-5 shows the IRI ranges represents by different road types and respective comfortable speeds [40]. Moreover, it is shown that for paved roads IRI is varying from 1.5 m/km to 10 m/km during the pavement service life. Further, it shows the increase of pavement roughness will reduce the speed drastically.

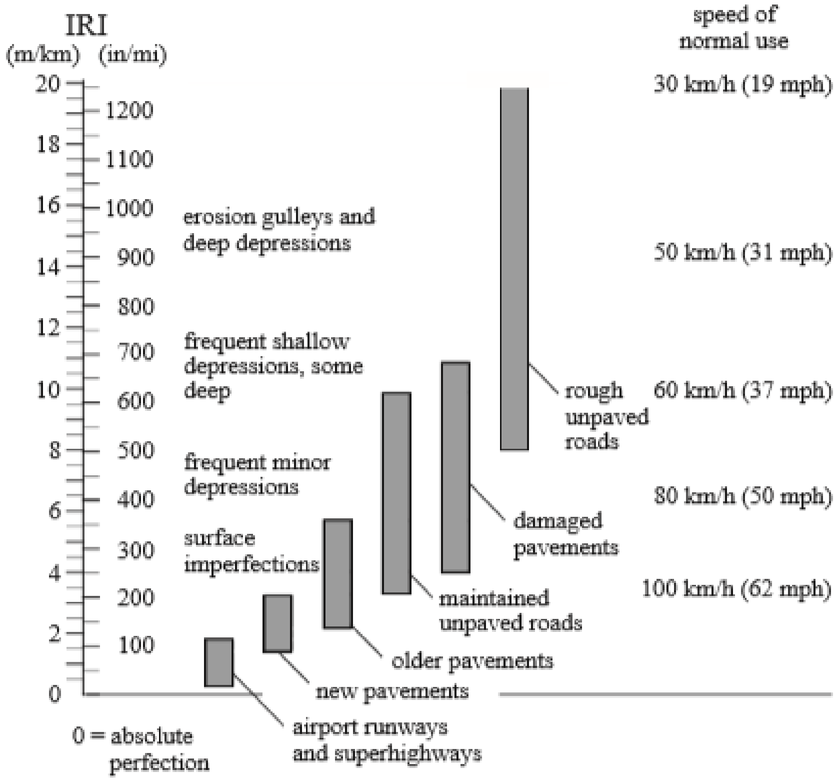

Figure 2-5: IRI Ranges for Different Road Types of with Comfortable Speed Limits [40]

There is a relatively higher correlation between IRI and the maximum comfortable speed for the road user. Table 2-4 shows the rough description of the IRI scale converted into relevant road defects and comfortable speed for the ride [41]. Table 2-4 is an illustrator of American Standard of Testing & Materials (ASTM) standard E1926-98, Standard Practice for Computing International Roughness Index of Roads from Longitudinal Profile Measurements.

Table 2-4: IRI Scale vs Comfortable Speed for User [41]

IRI Value (m/km)	**Comfortable Speed**	**Description**
2	Over 120 km/h	Very smooth
4	100 – 120 km/h	Smooth
6	70 - 90 km/h	Perceptible movement
8	50 – 60 km/h	Some swaying and wheel bounce
10	40 – 50 km/h	Significant swaying
12	30 – 40 km/h	Consistently rough
14	< 30 km/h	Very rough

Structural Capacity evaluation indicates the load-carrying capacity of the road pavement. The structural data is collected typically in project-level evaluation by using destructive and non-destructive methods. Deflection which is measured using Falling Weight Reflectometer (FWD) is the most common device used to calculate the structural capacity by calculating the load transferred to the structural layers. Deflection is the measurement of the vertical distance due to the dynamic or static load at a point [42]. Moreover, Benkelman Beam which is a simple device that operates on the lever arm principle also used to measure the pavement deflection.

Skid resistance is the force developed to wheel prevent from rotating when that slides along the pavement. Skid resistance is measured in terms of Skid Number (SN) which is dependent on the micro-texture and macro texture [42]. There are several skid resistance measuring equipment are available such as the Portable Pendulum Skid tester, The locked wheel tester, etc.

The characteristics of the equipment used for the pavement condition evaluation are described in Table 2-5.

Table 2-5: The Characteristics of Equipment Used for the Pavement Condition Evaluation

Name of Equipment	Operation Principal	Output	Operating Speed	Advantages	Drawbacks
Laser Road Surface Tester (LRST)	Measures slope profile in the time domain	Distress Unevenness, IRI	Up to 90 kmph	Suitable for all-weather condition	Calibration is needed regularly for laser and accelerometer
Automatic Road Analyser (ARAN)	Continued images one forward and two straight down	Videotapes of distresses	30-100 kmph	Covers about 600 km a day with good accuracy	Expensive Manual processing
Falling Weight Deflectometer (FWD)	Elastic deflection under impulse load	Deflection	200-300 Stations per day	Easy to operate relatively fast Complete deflection profile is measured	Expensive
Benkelman Beam	Elastic deflection under static load	Rebound deflection at the single point under load	Crawling	Simple, quick, cheap	Single point deflection
British Pendulum Skid Tester	Measures lateral friction by swing action	Skid resistance	Very slow	Simple, portable	Noting and recording manual spots measurements only
DIPSTICK	Measures vertical profile by slope measurements	IRI	Slow walking	Measures true profile	Very slow
Mu Meter	Measures side force coefficient	Friction value	Up to 150 kmph	Requires little traffic control	Ineffective in winter Sharp curves and steep grades
Bump Integrator	Bumps in cm or pulses and corresponding road length in meters	IRI	Greater than 10 kmph	Can be used in extreme and rugged road conditions Low cost compared to other vehicle-mounted accelerometer-based equipment Quick and easy installation, full serviceability in the field	Not repeatable changed the characteristics over time Require regular calibration

Further, various composite indicators and user perception-based rating methods were developed to evaluate pavement condition, such as pavement condition index (PCI), present serviceability rating (PSR), roughness index (RI), remaining service life (RSL), etc [43]. Thube et. al. (2007) derived present serviceability index (PSI) and PCI-based composite pavement deterioration models for LVRRs of India [44]. A complex prioritization index called Modified Maintenance Priority Index (MMPI) is developed to overcome the issues with exiting maintenance prioritization methods for LVRRs [45]. The index is a combination of deflection and roughness measurement primarily while introducing maximum permissible value. In addition to that traffic volume, rutting and fatigue failures are considered in developing the index.

Further, the Analytical Hierarchy Process (AHP) is used as a multi-criteria decision tool to prioritize maintenance strategies [35, 46, 47]. The results from AHP indicated that unevenness, skid resistance, bearing capacity (CBR value) are the best indicators and raveling, rut depth, pothole are the type of distresses most important in evaluating pavement condition in the rural road network [47]. Based on the defined weights for each distress and rating, they defined pavement performance index (PPI) to evaluate pavement condition which is shown in Equation 1.

$$\mathrm{PPI} = \sum_{i=0}^{n} W_i R_i \tag{1}$$

Where: PPI - pavement performance index, R_i - the rating of each deterioration parameter, W_i -Weightage of each deterioration parameter

Base failure index (BCI) along with PCI is used to investigate rural asphalt road conditions based on matter element analysis [48]. The analysis process is divided into two parts as establishing matter-element and establishing a classical, segment field. Establishing the matter-element field is described as evaluation levels with BCI and PCI as shown in Equation 2.

$$R_n = \begin{bmatrix} M & C_1 & X_1 \\ M & C_2 & X_2 \\ M & C_3 & X_3 \end{bmatrix} \tag{2}$$

Where: C_1- pavement surface condition index (PCI), C_2 - base failure index (BCI). M - excellent, good, middle, bad, poor, five evaluation levels, X - the value of things M about the characteristic C, that is, PCI and BCI on five levels of the score range.

As described earlier, some data type has more significance with the use of it in either network level or project level. Project-level data are more detailed than network-level data. Moreover, project-level data types can be used for establishing intervention levels and to refine network-level maintenance management treatment recommendations [49]. On the other hand, network-level data types are used for activity planning and prioritization. Table 2-6 is illustrated the data types used at the network level and project level respectively.

Table 2-6: Comparison of Network Level vs Project Level Data Types [49]

Network Level Data Inventory Types	**Project Level Data Inventory Types**
International Roughness Index (IRI)	Soil Characteristics
All Cracking Types	Structural capacity
Rutting	Detailed crack mapping
Surface Disintegration	Drainage condition
Joint condition	Guard & sign details
Geometric Data	Geometric Data
GPS Coordinates	
Road signals	

Geographical Information System (GIS) and remote sensing techniques were used in [50], to demonstrate and assess the rural road network of Nebilyer district in terms of present condition measurement. Further, a quick and simple rural road condition measurement method was developed in [51] based on simple evaluation criteria. A hierarchical structure is developed by identifying different indexes as traffic safety index, drainage condition index, overall pavement index, etc.

2.3.1 The Relationship between IRI with Distresses

The relationship between surface distress and roughness in LVRRs provides useful information for the operation level of PMS and accurate pavement design method development. It is understood that from the study conducted in [51], the sensitivity of IRI with observed distresses indicated that pothole propagation and cracking initiation in IRI 5.4 m/km and 5 m/km respectively. Effect of raveling of asphalt concrete pavement on IRI was established in [52], from distress surveys conducted in different highway classes confirms a strong relationship with a coefficient of determination (R^2) of 0.8 to 0.92 (power, exponential, polynomial functions). Pavement roughness development is a result of distress progression which is modeled in HDM-4 software [53] as shown in Equation 3.

$$\Delta \mathrm{RI} = \mathrm{K_{gp}} + \Delta \mathrm{RI_S} + \Delta \mathrm{RI_C} + \Delta \mathrm{RI_r} + \Delta \mathrm{RI_t} + \Delta \mathrm{RI_e} \tag{3}$$

Where: Kgp - calibration factor of general surface roughness development, ΔRI - gradual increase of pavement surface roughness, ΔRIs - structural pavement deterioration, ΔRIc – deterioration due to cracking, ΔRIr – deterioration due to rutting, ΔRIt – deterioration due to potholes, ΔRIe – deterioration due to climate effects

Cracks are vital distress type which indicates surface, and underneath layers' failure. The profiler with laser sensors is capturing cracks accurately than the other roughness measuring equipment, by inducing spikes in a shorter time [54]. There would be a relatively higher IRI in the profilers which are sensitive to cracks and two main reasons are there for that; IRI increment due to crack is not perceived by the traveling user and the effect is not completely repeatable. Even though that the study was conducted in India [51], showing that the roughness value is increased by 0.25 m/km with the increase of 1% area of cracking when IRI value greater than 5m/km. Moreover, alligator cracks are found to be more contributed to roughness progression than other cracking types of longitudinal cracks and block cracks [55]. The regression model developed by Lin et al, (2003) [56], which is shown in Figure 2-6, provides sufficient evidence that cracking shows a good relationship (R^2=0.927) with IRI progression.

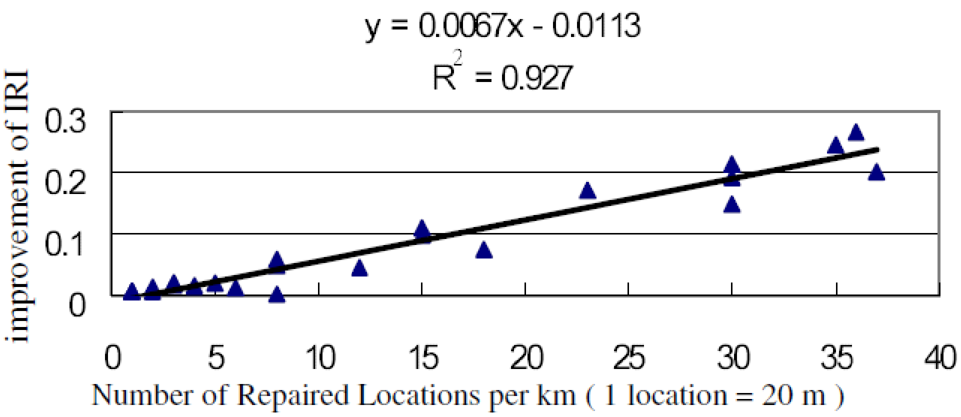

Figure 2-6: IRI Progression with the Cracking [56]

In LVRRs, the pothole is considered as the dominant distress type and especially as the indicator to identify a failed road. It was observed that from most of the analysis, the pothole is the primary explanatory variable of the roughness. Measuring potholes in these IRI prediction models is done in two ways; either in terms of percentage area of the segment total area or number of the pothole with the reference to defined standard size [51,56]. In the counting potholes, few defined it as low, mild or severe potholes based on the area and pothole depth [43,57], while others focused on the standard size of pothole [58]. Moreover, the study conducted recently, found that potholes along with cracks are provided roughness prediction accurately with high precision (R^2=0.81) [55]. The pothole is a more sensitive distress type to IRI than most of the distresses because even a small change in pothole density would increase roughness rapidly (0.12 m/km per 1% area increase) as in Figure 2-7[51].

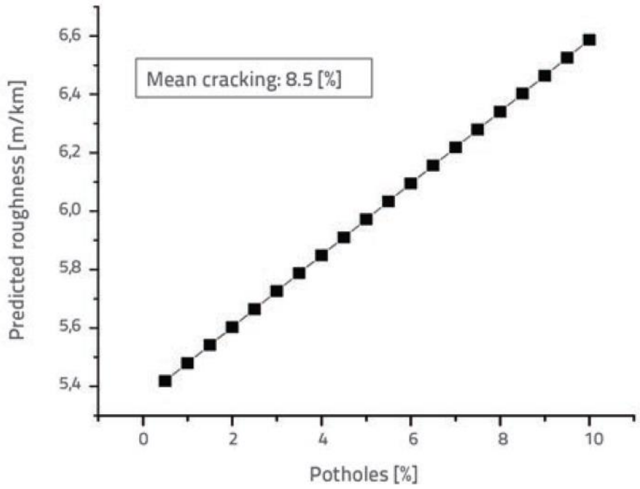

Figure 2-7: Plot of Arbitrary Pothole Values and the Corresponding Roughness Values for Sensitivity Analysis [51]

Raveling is a key distress type especially in LVRRs, which can be observed regularly which is known as the loss of pavement material due to asphalt handing effect due to aging, poor compaction, etc [59]. The severity of raveling would be increased with the loss of fine and coarse aggregates; hence this distress type also contributes to the IRI progression. The study conducted by Mubaraki, 2016 shows that raveling density has shown a good relationship with roughness increment as shown in Equation 4 [60].

$$\text{Raveling} = 28.2 + 9.00 \log \text{IRI} \tag{4}$$

In addition to the above distresses, edge failures (edge cracking, edge breaking & edge gap) are also considered by several researchers, in their models [57]. The pavement edges (usually one foot from the edge) are cracked or break due to insufficient shoulder support or poor drainage facility mostly [61]. The PAVER system also introduced five roughness-related distress; Bumps and sags, Corrugation, Railroad Crossing, Swells & Shoving [62]. Moreover, the study done in Taiwan has found that Digging/Patching shown a good correlation with IRI, in addition to pothole & rutting [56].

The capability of IRI to reflect the overall pavement condition is evaluated by several researchers by finding the combination effect of distresses with IRI. Several analysis methods have been used in that manner, namely multiple linear regression modeling, Artificial Neural Network (ANN) analysis, Multivariate Adaptive Regression Splines (MARS) method, Fuzzy Logic approach, Probabilistic modeling, etc [55].

Multiple regression analysis is the most common/ traditional method used to express a dependent variable (in these approaches roughness or IRI) within several independent variables (e.g.: distresses). Moreover, non-distress-related factors such as environmental factors, pavement age, traffic volume are included in some researchers in their regression modeling.

Al-Omari and Darter (1995), developed a regression model for asphalt pavements between IRI and the pavement serviceability ratio (PSR), which included distress types; rutting, deformations, patches, and cracks [59]. Moreover, for concrete pavements, the researchers identified that joint faulting, transverse cracking, and joint spalling shown a strong correlation with IRI. Aguiar–Moya et al. [63] developed a Mechanistic-Empirical (M-E) regression model of IRI with longitudinal and transverse cracking, block cracking, fatigue cracking, and rutting. In addition to the distress types pavement age, precipitation rate, and the mix design parameters are used as independent variables. Mactutis et al. (2000), [64] developed a linear regression model which describes the relationship between IRI and the mean rut depth and the crack %. The relationship appears to have a very good relationship with the regression coefficient (R^2=0.71). It is reported that fatigue cracking is more sensitive to roughness than rutting and the roughness relationship is illustrated in Equation 5.

$$\mathrm{IRI} = 0.591\mathrm{IRI}_{\mathrm{Initial}} + 0.0094\mathrm{Fatigue\%} + 0.00847\mathrm{RutDepth} \qquad (5)$$

Where IRI is in m/km and Rut Depth is in mm.

Another multi-variable regression model between the IRI and the distresses is developed by the Rajasthan, India [63], which shown that cracking, raveling, potholes, patching, and rutting are the major distress types that contribute to the roughness increment. The model interprets that, IRI predictability is high for potholes since it has a higher coefficient than other distress parameters. Moreover, patching shown moderate significant in the multiple regression model and the other distresses shown low coefficient in the model, hence significant is low.

Fuzzy Logic models are mathematical tools that deal with uncertainty. Generally, the logic is behind this is the measuring of the chance of a given event expected to occur, if an event is already occurred [65]. A Fuzzy logic system is used to map an input data set to get a scalar output and the fuzzy logic [66–68] approach, is helpful for the evaluation of various data types such as numerical and verbal. The study conducted in India used Rut depth (in mm), Total crack area (in m^2), pothole area (in m^2), patchwork (in m^2) & raveling (in m^2) as input variables to predict IRI (in m/km) as the output variable. It was found that the prediction model shown a strong correlation with an R^2 of 0.98 concluded that The limitations of traditional regression models can be overcome with the use of tools such as Fuzzy Logic models [69].

The ANN technique is another approach used by many researchers to predict the combined effect of distresses on IRI. During the conducted studies, it was noted that the ANN methods are also preferred due to a large number of independent variables while some of the variables are difficult to express numerically [70-72]. Lin et al. developed a model by using the ANN technique, which is capable of estimate the IRI value on a pavement by 14 distress parameters; including pothole, rutting, cracking, digging/patching, etc [56].

Studies which used the ANN approach in the investigation of the relationship between surface distress and performance are striking. Lin et al. developed a model, using the ANN technique, with the capability of IRI estimation with fourteen surface distress inputs, consisting of the road level, left rutting, right rutting, alligator cracking, cracking, digging/patching, potholes (mild and severe), patching, bleeding, corrugation, stripping, and man-holes (mild and severe) [56]. The study is rare in the practice that used a large amount of data as the input. Moreover, Chadra et al. developed models using regression and ANN between IRI and five types of surface distress; rutting, cracks, potholes, patching, and raveling [73]. The estimation capabilities of the models developed in the study, ANN is identified as the most efficient method.

There are several studies is conducted to find the sensitivity of IRI with distresses and applicability as a pavement condition evaluation parameter is shown in Table 2-7.

Table 2-7: Summary of Studies Conducted to Evaluate the Relationship between IRI and Distresses

Country/ Analysis Method	**Method of IRI Measurement**	**Key Findings**
Saudi Arabia [60]/ Multivariable regression analysis	Automatic Road Analyzer (ARAN) system consists of accelerometer and roughness laser	R^2=0.3 for functional model Raveling, cracking have shown good significant Rutting has shown low significant
		Model-1: IRI=4.498+0.0096CRA+0.0083RUT+0.0067RAV Model-2: IRI=3.58+0.0077CRA+0.0054RAV
India [57]/ Multiple-linear regression	Bump Integrator	R^2=0.66, Mean Absolute Percentage Error (MAPE)=9.8% High severity edge cracking, high severity alligator cracking, Medium severity pothole predominant
		IRI_D (m/km) = A + 0.318*ACL + 1.205*ACH + 0.120*L/T CL + 0.041*L/T CM + 0.023*RH + 0.698*PL + 1.189*PM + 0.125*PAH + 3.00*ECH + 0.162*EBL + 0.269*EBM + 0.145*EBH
Rajasthan, India [63]/Multiple -linear regression	Bump Integrator	R^2=0.99, The pothole is the most influenced distress, patching is moderately significant, cracking is sensitive to severity level
		IRI (m/km) = $IRI_{initial}$ + 0.0143*RLp + 0.216*RMp+ 0.0345*RHp + 0.0303*PALp + 0.0418*PAMp + 0.0432*PAHp + 0.111*PLp + 0.151*PMp + 0.178*PHp + 0.0103*CLp + 0.0156*CMp + 0.0103*CHp + 0.0018*RULp + 0.0023*RUMp + 0.0034*RUHp
Turkey [55] / Multivariate Adaptive Regression Splines (MARS) Approach	Image processing system using high-resolution (HD) cameras	R^2=0.74 Alligator cracking, depression and patching have shown the highest influence on increasing IRI up to 500%
		The mathematical model is developed adding 67 basic functions, with 29 independent variables.
Taiwan [56] / Back-propagation neural network methodology	Automatic Road Analyzer (ARAN) system consists of accelerometer and roughness laser	R^2=0.89 Severe pothole, Digging/patching, rutting has shown the highest correlation Bleeding, road level is shown least correlation
		Sigmoid transfer function = 1/[1 + exp(-x)] Where, x- distress variable with the severity level
Iran [74] / Regression analysis	A smartphone which embedded accelerometer sensor and Road surface profiler	Good correlation (R=0.91) between IRI measured by smartphone and Traveler's opinion (functional condition)
		IRI = 4.19∗RMS+1.73; RMS - root mean square of acceleration data

IRI_D refers to IRI due to distress; ACL & ACH refers to low & high-level alligator cracking % area; L/T CL & L/T CM refers to low & medium level longitudinal/transverse cracking in meters; RH refers to high-level raveling in % of the area; PL & PM refers to low & medium level potholes % of the area; PAH refers to high level patching % of the area; ECH refers to high-level edge cracking in meters; EBL, EBM & EBH refers to low, medium & high-level edge break in meters [57].

$IRI_{initial}$ refers to initial IRI, $IRI_{initial}$= 2.4m/km for National Highways, $IRI_{initial}$= 2.8m/km for State Highways, $IRI_{initial}$= 3.0m/km for Major District Roads; RLp is low severity raveling in % of the area; RMp is medium severity raveling in % of the area; RHp is high severity raveling in % of the area; PALp is low severity patching in % of the area; PAMp is medium severity patching in % of the area; PAHp is high severity patching in % of the area; PLp is low severity potholes in % of the area; PMp is medium severity potholes in % of the area; PHp is high severity potholes in % of the area; CLp is low severity cracking in % of the area; CMp is medium severity cracking in % of the area; CHp is high severity cracking in % of the area; RULp is low severity rutting in meters per km; RUMp is medium severity rutting in meters per km and RUHp is high severity rutting in meters per km [63].

The pavement roughness can be related to the overall pavement condition as shown in Equation 6, by finding the relationship between IRI and PCI. This model was developed by measuring distresses then converted to PCI value, using long-term pavement performance (LTPP) data gathered from 20 pavement sections in 11 states in the USA [58].

$$\mathrm{PCI} = \mathrm{K_1 IRI^{K_2}} \tag{6}$$

Where PCI is the pavement condition index; IRI is the international roughness index in-unit m/km; K_1 and K_2 are the constant values 2 and -0.481 respectively.

Pavement Roughness is a functional performance indicator of a road that can represent the composite behavior of distress. Pavement Condition Rating (PCR) is a global parameter as shown in Equation 7, is a combination of Roughness Condition Index (RCI) and PCI indicator. The outcome from the study conducted by Yeganeh *et al.* 2017, shows that the use of RCI has improved the capability of prediction of functional performance in the network level planning [74]. The RCI which is derived from IRI is illustrated in Equation 8. The results have shown that its ability to be used as the first screening tool to identify the most suitable treatment on a particular pavement section.

$$\mathrm{PCR} = 0.6\mathrm{PCI} + 0.4\mathrm{RCI} \tag{7}$$

$$\mathrm{RCI} = 253.67\mathrm{e}^{-0.459\mathrm{IRI}} \tag{8}$$

Pavement condition score (PCS) is a combination of distress pothole, rut and cracks with defined weightages [58], PCS index shown a strong correlation of 0.79, which provides evidence that roughness is a good substitute for visual condition measurements and the relationship shown in Equation 9.

$$\mathrm{PCS} = 83.792 - 5.226\mathrm{IRI} \tag{9}$$

Where PCS is the pavement condition score.

2.3.2 Smartphone-based Roughness Measurement

The ASTM standard E 950 defines roughness measurement into four categories from Class I to Class IV according to their sampling interval, vertical measurement resolution, precision, and bias [75]. Generally, class I & class II profilometers are measured the actual road profile/geometry with a high precision level. Class III equipment is provided response type measurement while class IV is categorized as subjective rating. The roughness measurement equipment categorization with examples is illustrated in Table 2-8 [76].

Table 2-8: Roughness Measurement Equipment Classification [76]

Type of Roughness measurement	**Description**	**Example**
Class I	Precision equipment that measures the true profile of pavements	Rod & Level, Dipstick, Profilometer Z-250, profilometer TRL, Walking Profilometer ARRB (Australian Road Research Board)
Class II	Higher precision, Labour intensive, low time efficient	Other Profilometers (Straightedge, Low-speed CHLOE, Contact & Non-contact inertial, Laser Profilometer,
Class III	Response type systems	Roughometer, Mays meter, Bump Integrator, MERLIN, Riley, Smartphone Apps
Class IV	Subjective Rating/Panel Rating	-

Roughness evaluation using the traditional Class I type equipment such as a laser profilometer is not generally adopted in LVRRs, especially in developing countries due to the high cost of the equipment and difficulties to use on the narrow roads. Even Class III type measurement equipment such as Bump integrator, Roughmeter is not commonly available in local agencies due to the cost and lack of technical expertise to operate. Even though most local authorities are lack technical knowledge, an accurate roughness value still can be predicted by visual inspection method, smartphone-based roughness measurement, etc [55, 74]. Therefore, several researchers have investigated the use of smartphone-based roughness measurement methods especially useful for local road agencies [76-79].

The Smartphones-based roughness measurement leverages the accelerometers inbuilt in smartphones to detect the vertical acceleration and the apps have been developed to estimate the roughness values based on the readings. 3-axis accelerometer, gyroscope and a Global Positioning System (GPS) are used to measure the road roughness [55]. There are several commercially developed software such as Roadroid App that can be used to evaluate pavement roughness [80]. As an example, concerning the difficulties to use full-size automobiles to measure the roadway roughness in LVRRs, Abulizi (2016), has introduced a low-cost method, consisting of two accelerometers set up to vehicle suspension system [81].

The system is named as a compact mobile profiler and from its vehicle acceleration profile converts into the roughness profile by inverse calculation of vertical displacement, then real-time data displayed on the screen. The back-calculation of IRI is obtained by the integrated simulation shown in Equation 10.

$$\mathrm{IRI} = \int_0^{\frac{L}{v}} \frac{\dot{X}_1 - \dot{X}_2}{L}\,\mathrm{dt} \tag{10}$$

Where; $\dot{x}_1, \dot{x}_2$ -The velocity of the sprung mass and un-sprung mass, L-Length of the measure, v-Mean velocity of the vehicle

Further, to measure the roughness in the network level, the smartphone is used with its embedded sensors which is a feasible alternative solution to the manual data collection and conventional roughness measurement. 3-axis accelerometer, gyroscope and a GPS are used to measure road roughness as a cost-effective method by Yeganeh et al, (2017) [74], while taxis consist of smartphones used to monitor the surface condition of the road network which can detect isolated potholes through the vertical vibration [50]. “Z-THRESH” determines a threshold for the z-axis accelerometer by capturing the pothole by outside data of the defined threshold. It also developed an algorithm to detect anomalies by indicating another threshold, in which all three-axis accelerometer values are close to zero gravity [77].

To check the suitability of smartphone-based roughness measurement, in [76], Root Mean Square (RMS) of vertical acceleration obtained from smartphone converted to IRI and the values compared with rod and level measurement. The vertical acceleration is provided a clear indication between a rough road and a smooth road as shown in Figure 2-8 [74]. The converted IRI value can be used to evaluate the ride quality. The results indicated that its applicability is high in a PMS for network-level evaluation since the variation is low as 3%-6% while Pearson correlation (r) is high as 0.97% to 0.99%. Vehicle acceleration data was used in the study conducted by Islam et al, (2014) [80] to obtain a pavement profile that is to be used in the proVAL software program. In the analysis stage, to convert the acceleration data into roughness, double integration is numerically conducted. As an application, a pavement roughness map is generated using project-level roughness measurement after being converted into a road roughness profile by MATLAB script [82].

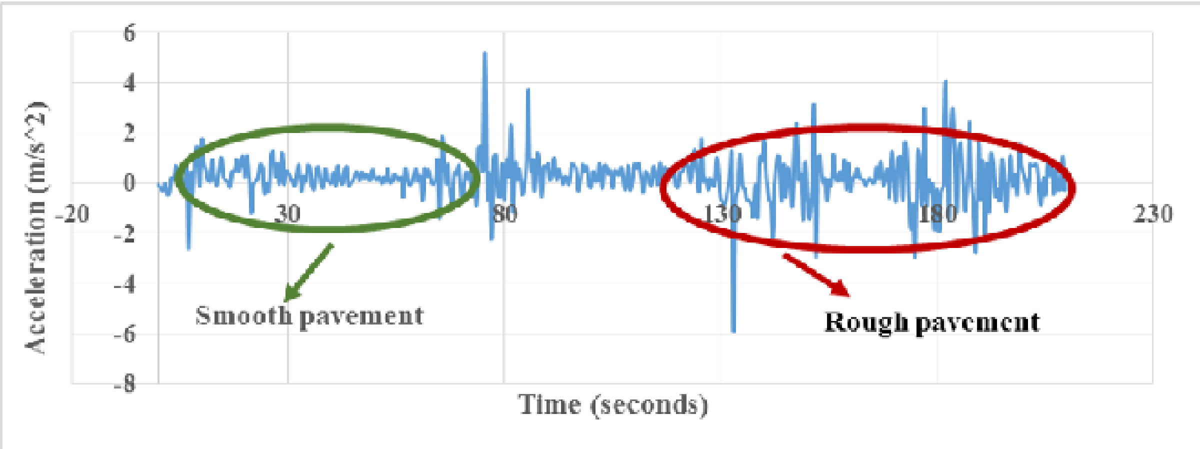

Figure 2-8: Sample of Accelerometer Outputs for a Route with Different Pavement Conditions [74]

In addition, distress detection methods have also been developed to identify distresses. Based on the amount and wavelength, distresses such as rutting, irregular patches, corrugations and potholes on the pavement surface can be captured accurately [78-80].

There are several studies were conducted to validate the applicability of smartphone-based roughness measurement for condition evaluation and the summary of the key finding of previous researchers are shown in Table 2-9.

Table 2-9: Summary of Results on Smartphone-Based Roughness Measurement

Data collection instrument	**Vehicles used**	**Measured IRI range**	**Speed of measurements**	**Key findings**
Smartphone model in HTC with video camera [44]	Toyota Hilux 4WD cab	1.5m/km-10m/km	20kmph-60kmph	• Correlation between IRI and resultant acceleration is range from 0.55 to 0.75 for different speed of the vehicle. • No significant variation with change in speed of a vehicle
Smartphone model in Samsung Galaxy S5 mini with accelerometer and GPS [76]	A passenger car	1m/km-16m/km	20kmph-60kmph	• Correlation of 0.97-0.99 with roughness measurements of rod and level method • Speed of measurement does not affect significantly on roughness measurements
Two Android smartphones and GPS logger with video recorder [83]	Toyota VIGO pickup truck and Toyota Camry car	1.5m/km-16m/km	10kmph-80kmph	• Correlation of 0.67-0.75 • Linear relationship is better representative • The relationship is considered strong when speed is less than 60kmph • Less importance on vehicle type and device
Samsung Galaxy S8 with GPS [82]	Chevy Traverse LT 2015 (Car)	Up to 3.6m/km	30kmph-100kmph	• Found a sound correlation of 0.8-0.85 between smartphone IRI and PCI
Smartphone application with GPS [74]	A passenger car	2m/km-12m/km	20kmph-50kmph	• Correlation of 0.76 between IRI vs RMS (root mean square) • Travelers’s opinion has also confirmed the applicability of smartphone IRI with a correlation of 0.81

The results of several studies conducted to validate the applicability of smartphone-based roughness measurements in Table 2 provide sufficient evidence on suitability for rural roads. The accuracy of the results shown less variation with the type of vehicle [84], the smartphone model [78] and the speed of the vehicle for data collection [83, 85].

However, there can be random errors that occur due to noise generated by the accelerometer itself. Moreover, resonant motions are produced due to inappropriate vehicle support, engine roar at high speeds, during a gear shifting or at horizontal and vertical curves (mainly with small radius) of a road. Recently developed smartphone apps can filter those effects in data processing [52].

In recent years, the Roadroid app which is an android-based application emerge as a roughness measuring tool among researchers, due to low cost, repeatability and portability [86]. Fortunatus et al, (2018) conducted a study to assess the applicability of Roadroid in LVRRs [86]. It was found that Roadroid IRI is repeatable and clustered within a narrow range with a lower Coefficient of Variation (CV) is shown in Figure 2-9.

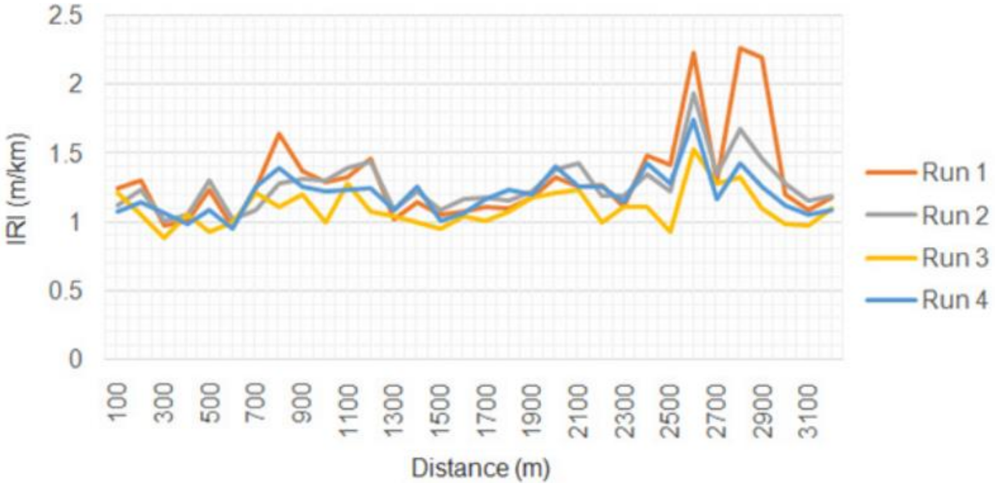

Figure 2-9: Repeatability of Roadroid IRI on Highway Section I-75 [86]

Further, the study has shown that Roadroid IRI underestimated the roughness measurement compared to the Profiler IRI which is shown in Figure 2-10. However, local road agencies with budget limitations can integrate Roadroid on their ride quality measurement in LVRRs [86].

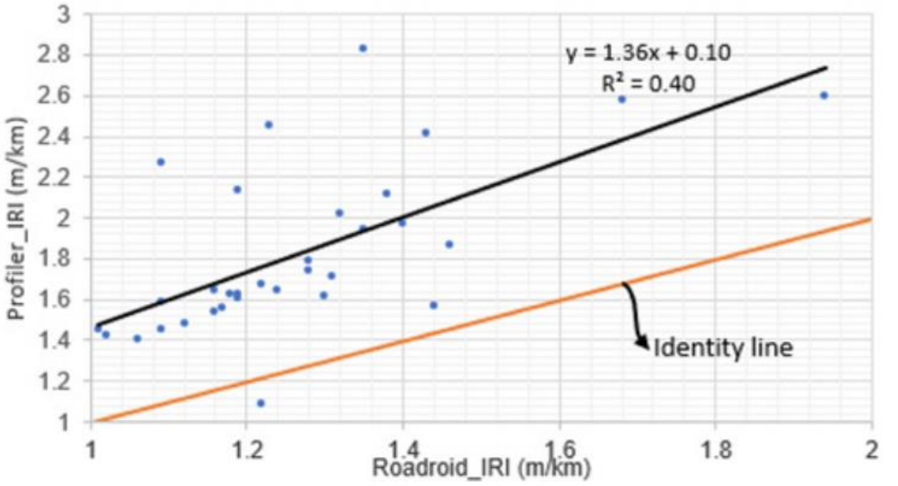

Figure 2-10: Relationship between Profiler and Roadroid Roughness on Highway Section I-75 North [86]

2.4 Prioritization Techniques in Pavement Management Systems

Prioritization is a process that provides a method to decide or select the favored objects out of many feasible options. The requirement for priority is not just to neglect the minimum imperative prerequisites, yet additionally to determine clashes and execute the arrangement [87].

In pavement management, the prioritization process can be utilized for choosing the pavement segments as elements to decide the best maintenance strategy. Ideally, prioritization is a consistent and justifiable process that involves minimizing the maintenance costs subject to keeping the minimum levels of serviceability. Prioritization is a complicated process that requires sound engineering judgment and a better understanding of local road network conditions. Current fiscal crises; the inability of the state to bridge a deficit between expenditures and its tax revenues have made prioritization decision making more important than past.

Numerous prioritization methods have been introduced which varying from a simple ranking on engineering judgment to broad optimization-based mathematical formulations. Those systematic processes determine the best projects to implement by listing the candidate sections for M&R work concerning pavement condition, traffic level, social importance, etc.

There are several prioritization techniques are available and can be adapted to the PMS decision-making process. Table 2-10 is illustrated the advantages and drawbacks of the different classes of methods used for the project prioritization in PMS [31].

Table 2-10: Advantages and Drawbacks of Various Prioritization Methods [31]

No.	Type of Method	Advantages	Drawbacks
1	Simple Subjective Ranking	Quick & simple method	Bias & Inconsistency; Far from the optimal
2	The ranking method is based on pavement condition analysis & traffic, with economic analysis	Reasonably simple	Far from the optimal
3	Optimization using heuristics including the benefit-cost ratio	Simple approach & suitable for microcomputer environment; near to the optimal solution	Reasonably complex to implement; Time consuming

4	Comprehensive optimization by mathematical programming	Effect of M&R strategy taken into consideration; able produce optimal program	Complex & computation demanding; Time consuming

In brief, this section reports a review on various prioritization techniques developed at global view recently by the researchers.

2.4.1 Worst First Approach

A typical approach is to classify tasks and manage the worst conditional sections, regardless of their impact on the overall road network conditions and repair costs. This technique is called the "worst first" prioritization ranking method. The "worst first" approach is logical in the social and economic perspectives, the worst road will be caused for the highest user costs and public protests and complaints. The "worst first" method does not consider the rate of deterioration of the road section and the cumulative efficiency of the maintenance process. It is a basic practice that most of the local authorities are following, paying little respect to the effect of overall network condition and maintenance costs. Several PMS in practice used this technique as a simple decision-making method [3, 88].

2.4.2 Direct Assessment Method

The direct assessment method is the strategy that a typical individual would use in need evaluation. In this method, to rank and rate 'n' number of items, would involve n(n-1)/2 number of comparisons. The main drawback of this technique is it requires a large number of comparisons to be conducted even for a small-scale problem. Moreover, it would not quantify the actual difference between the alternative solutions which caused a significant error of the outcome in many situations.

2.4.3 Evaluate Factors Using Goals

This technique is simplified by getting ready an appraisal chart that lists every undertaking with applicable goals. This table includes the scoring system, definitions of goals and project. The method used to create this appraisal table should be easy and user-friendly. Once the goals are determined and the scoring system is selected, the assessment of the project is continued straightforwardly. Each item uses the selected scoring system to rate each goal. Multiply the item score for each goal by the appropriate weighting factor and determine the sum of the scores for each item and the highest project score ranked first [89].

2.4.4 Reverse Prioritization

Instead of ‘worst first’ methods some highway agencies have adopted a "reverse-first" strategy to overcome the problems encountered [90]. In the state where the maintenance cost is effective, the highest level is assigned to the road surface portion, so that the effect of performing the road surface repair is produced while reducing the maintenance cost. Since PMS are involving multiple objectives, this method may not optimize other objectives such as safety, pavement condition.

2.4.5 Analytical Hierarchical Process (AHP)

AHP is an important prioritization tool that is a mathematical method for multi-criteria decision-making. AHP was developed by Saaty (1980) as an effective tool for decision-makers to choose the best option [91]. It has been found that the application of the analytic hierarchy process (AHP) is valuable in general transportation-related decision problems. Tsamboulas and Yiotis (1999) conducted a comparative analysis of five multi-criteria methods for assessing transport infrastructure projects, including AHP [92]. The technique is making pair-wise comparisons between standards and alternatives, the common problems of the most advantageous alternatives are eliminated. The pairwise comparison is fully consistent with human behavior and reduces the dependence of decision-makers on their intuition.

Generally, in national road network-level analysis, socio-economic importance is rarely taken into the consideration. But when it comes to LVRRs, socio-economic importance plays a vital role because most of the LVRRs are located in rural areas. Several researchers have been used social and economic aspects in their prioritization models.

Federal Highway Administration, US DoT states that the importance to introduced key societal factors such as land use, access, aesthetics & economic consideration namely net benefit, LCC in maintenance decision-making [93]. Gunasoma & Pasindu, 2018 used socio-economic factors in the prioritization model namely connectivity to the local road network, land use pattern and importance to the community [46]. In that study, AHP is used as the prioritization technique and it was found that with the use of those aspects, better overall network performance can be achieved in maintenance decision-making.

Most importantly, traffic volume can be identified as the main priority factor for the prioritization analysis approaches which is used by several researchers in various countries [5].

Moreover, Climate condition, road functional category, population density are the other factors used as priority factors.

The study conducted in West Bengal, India has proposed seven techno-economic factors in prioritization such as Volume/Capacity ratio, Number of Commercial vehicles per day, Reduction in journey speed, Population served by per km road, Growth of Per Capita Income (PCI) in influence area, Growth of Net State Domestic Product (NSDP)/Net District Domestic

Product (NDDP) and potential safety hazards [94]. Moreover, the strategic factors related to connectivity for different road networks are also considered during prioritization. In most of the studies, at first, the relative weightages of socio-economic factors are calculated and then the priority index was calculated.

2.5 Optimization Techniques in Pavement Management Systems

Optimization is maximizing of minimizing an objective function such as pavement condition, safety improvement, socio-economic importance which are consist of binary, integer, or real-valued decision variables by incorporating equality or inequality constraints [5]. In pavement management, the problem involving included either single or multiple objectives functions with several constraints in real-world problems. Moreover, the intend of optimization is not just the solving a mathematical model, but it should address the problem related to engineering, socio-economic sense, environmental view, etc. The concern in solving an optimization problem is the existence of a large amount of M&R decision variables to decide [95]. Therefore, most of the researchers have been used a macroscopic approach rather than microscopic to reduce the number of decision variables [96].

Optimization of pavement maintenance expenditures can be conducted at either the network- or the project level. Network-level optimization focuses on the overall pavement network condition and budget allocation, which is handled with the global view of the entire pavement network [3, 97]. In project-level optimization involves the identification of subsections of the entire pavement network and produces an M&R strategy for each pavement section [97]. The network-level optimization is usually employed by a "macroscopic" approach, while project-level optimization is generally implemented by a "microscopic" approach, in which each pavement section is assigned a decision variable and if the variable is 1, the treatment is recommended for this pavement section, otherwise, it is 0.

The most usually utilized mathematical programming strategies for pavement management are linear programming, nonlinear programming and heuristic, integer programming, optimal control theory, dynamic programming, and Genetic Algorithm (GA) [6]. Due to the complexity of the optimization problem in pavement management, all of the above techniques are considered feasible only up to some extend & situations. Further, the optimization problem-solving techniques that are commonly used globally are briefly described below.

2.5.1 Integer Programming

Integer programming is the most common optimization algorithm used in pavement optimization models. Selecting a suitable algorithm is essential for an effective optimization tool. Integer programming is a dominant mathematical approach used to deal with the best way to allocate limited resources. The objective functions used in linear programming should be linear and even though there are many algorithms developed still many researchers are using linear programming models due to their simple approach. Many researchers such as Golabi et. al., (1982); Perera et. al., (2019) have developed network-level optimization models using integer programming [3, 98]. However, in such situations, this approach results in a large number of variables and makes the optimization model difficult to solve, especially for a large pavement network. Therefore, it is often used when the number of road sections is low.

2.5.2 Dynamic Programming

Dynamic programming is utilized as a part of circumstances where an expansive number of successive decisions are required. This optimization method begins with the desired final solution and finds the ideal estimation of the variable. There is no exact formula for this method and the problem is divided into several stages, each stage needs to decide, and the solution search process is continuing until the optimal strategy is finds. Every time a problem changes, the formulation is needed each time and there are many stages in the large problem [61]. Moreover, this approach is used in MOO along with the Pareto concept [99].

2.5.3 Artificial Neural Networks (ANNs)

Neural networks can be trained by using examples therefore, this system can be used to simulate decisions. After the training phase, it provides scores for the sections based on their condition. And neural systems help to recreate designs and sum up. Those are not ensuring the relevance of the choices made and behave as “black boxes" and are not conceivable to effectively extract the path followed by the interpretation of the solution [100].

These models consist of a large number of nodes and each node is associated with a state variable and an activation threshold. Each link between nodes is associated with a weight, and the state of the node is determined by the activation function. Being able to solve a combination problem that can handle a large number of decision variables ANNs reduces computational complexity but is slow in the training phase [5].

2.5.4 Genetic Algorithm (GA)

PAVENET developed by Chan et al, 1994 [21], is the first PMS that uses the GA as the optimization model. It is shown that the use of multi-year planning optimization problems achieved in certain accuracy in a relatively shorter time due to its heuristic nature.

The problem-solving process of GA starts with identifying the problem parameters and the genetic representation. Then, the search process of GA for a solution that best satisfies the objective function involves generating an initial random pool of feasible solutions to form a parent solution pool. That is followed by obtaining a new set of solutions then forming new parent pools through an iterative process. The fitness value or convergence criteria can be established, then it has the capability of producing optimal or near-optimal solutions for a road network. The entire solution searching process is repeated until the predetermined convergence criterion is reached. The general framework of GA in the optimization problem is presented in Figure 2-11.

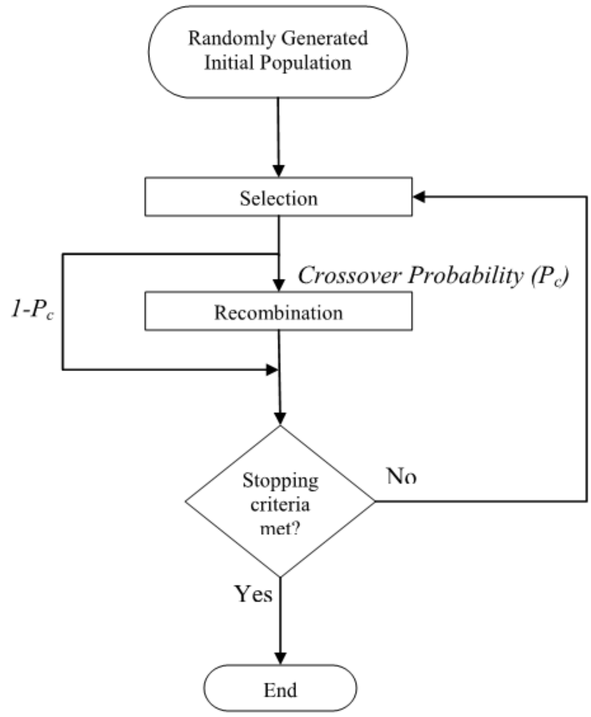

Figure 2-11: The General Framework of Genetic Algorithm in Solving Optimization Problem

Several researchers have found that GA produces a satisfactory level of results to pavement management optimization problems, therefore it is considered as the prominent class of technique due to its natural selection of the optimal solution.

Further, the summary of various optimization methods used in PMS is presented in Table 2-11.

Table 2-11: Summary of Varies Optimization Methods

Method	Description	Advantages	Disadvantage/ Limitation
Integer Programming [19,101,102,103]	Objective functions & constraints are presented in either linear programming & non-linear programming Only Binary decision variables can be applicable (0 or 1)	• Suitable for network-level approach • Realistic as do-or-nothing scenario	• Difficult to handle a large number of the decision variable • Difficult to ensure that the solution is optimal or not
Dynamic Programming [99,104]	No standard formulation to solve the problem The problem is divided into several stages and in each stage, decisions are taken separately	• Can be used in multi-year problem • When decision takes in sequence dynamic programming is the ideal	• Every time a problem change new formation should be implemented • For larger problems, many number of stages are required
Artificial Neural Network (ANN) [72,77]	The model consists of a significant amount of nodes Each node comprises a variable and a threshold The activation function determines the weighted state of each node	• Combinational problems can be handled • Handle a large number of variables • Computational complexity is reduced	• Slow in the model training process • Difficult to understand the network learning
Genetic Algorithm (GA) [5,17,21,105,106]	Random selection with a pool of solution by mutation and crossover operations	• Can be easily defined objective functions & constraints • Combinational problems can be handled • Can handle a larger number of variables • Computational complexity is reduced	• Renders near-optimal solutions

Therefore, from literature reviews, it can understand that using prioritization and optimization tools in maintenance decision-making would be more realistic while finding the best program without imposing unnecessary constraints or subjective rating. The analysis presented in the National Cooperative Highway Research Program (NCHRP) in 1995 showed that the use of priority ranking approach in the project prioritization process is effective around 20% - 40% than the subjective selection of M&R. Moreover, the use of macroscopic optimization tool such as GA heuristic in-network level is increased the effectiveness further in 10%-20% range [107].

2.6 Pavement Performance Evaluation & Maintenance Interventions

Pavement performance models are developed in terms of roughness, distress, deflection, friction, etc. Figure 2-12 illustrated the assets performance curve which represents the life cycle of a pavement itself.

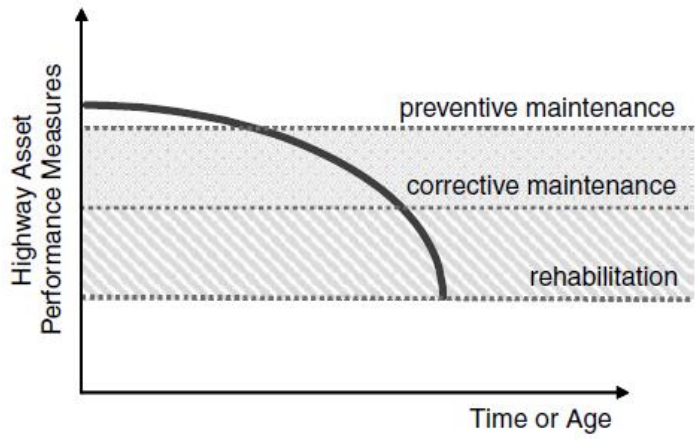

Figure 2-12: Asset Performance Curve for a Pavement Section in The Life Cycle

Most of the researchers are selected roughness as the main indicator to evaluate pavement performance due to its repeatability and ability to access overall pavement condition. The developed prediction models can be classified into two categories as deterministic and probabilistic models [101]. The deterministic models are either empirical or M-E models consisting of the primary response, structural performance, functional performance, and damage models [108]. The probabilistic models include Markov chain (MC), Bayesian regression, and survivor curves [101,109]. The roughness prediction models developed by several researchers by considering climate condition, traffic density and road type as shown in Table 2-12.

Table 2-12: Pavement Performance Prediction Models Developed in Worldwide

Reference	Type of Model	Factors Used	Key Findings
George [110]	Empirical	AC overlay thickness, (TOPTHK), CESAL, Pavement age	Regression equation: $IRI = (3.095 + Age^{0.3571} (1+CESAL^{0.3054}))\ TOPTHK^{-0.3235}$ Pavement age is the most significant predictor of deterioration. Power models were found to be the best representation.
Prozzi & Madnat [111]	Mechanistic -Empirical	Equivalent asphalt thickness (EAT), Layer thickness (H), frost gradient (G)	Model: $r_{it} = \theta_1 e^{\theta 2.\ H1i} + \sum_{l=0,\ t-1} (\theta_3.\ EAT_i^{\theta 9}.\ e^{\theta 10.\ G1}.\ N_{il}^{\theta 11}.\ \Delta N_{i,l+1})$ Two IRI deterioration stages were found as linear and non-linear by the joint estimating
Soncim et. al. [112]	Probabilistic	Traffic density, climate, Initial IRI (set between 1.5 to 2.0m/km)	Probability Matrix: $P_{ij}^{(t)} = \sum_{k=0,\ m} P_{ik}^{(v)}.\ P_{jk}^{(t-v)}$ Roads located in rainy regions with higher traffic density present an accelerated deterioration rate After IRI 6m/km was reached, the deterioration rate increased
ARA, Inc. [113]	Mechanistic -Empirical	Pavement age, fatigue cracking $(FC)_T$, transverse cracks $(TC_s)_H$, Patches $(P)_H$, Freezing Index (FI)	Model: Bituminous treated base $IRI=IRI_0+0.0099947(age)+0.0005183(FI)+0.00235(FC)_T+18.36\{1/(TC_s)_H\}+0.9694(P)_H$
Paterson [114]	Empirical	Structural Number (SNC), ESAL, pavement age, Wearing course type	Regression Model: $IRI=[IRI_0+725(1+SNC)^{-4.99}\times ESAL]\times e^{0.0153AGE}$

2.6.1 Work Intervention Criteria & Threshold for Maintenance Activities

There are various categories of pavement maintenance activities used globally, with all maintenance activities to extend the life of the pavement. The concept is connected with related categories, including pavement preservation, rehabilitation, and reconstruction. The definitions are used by the FHWA state that three main categories as follows [115];

1. **Pavement preservation**: Activities employing a network level, long-term strategies that enhance pavement performance by using a set of pavement treatments that extend pavement service life, improve the user safety performance, and fulfill road user objectives.

2. **Pavement rehabilitation**: Structural improvement would extend the service life of the pavement by improving the load-carrying capacity.
3. **Pavement reconstruction**: Replacement of the entire pavement structure by replacing an equivalent or increased pavement structure.

Pavement maintenance is distinguished from pavement rehabilitation & reconstruction because maintenance treatments do not significantly improve the structural capacity. Preventive maintenance is the largest component of a pavement preservation program. Following definitions, the FHWA uses for different categories of preventive maintenance [116]:

1. **Preventive maintenance**: This type of practice is focused on retards future deterioration and maintains or improves the functional condition without significantly increasing the structural capacity. Preventive maintenance should be applied to pavements in relatively good condition having a significant amount of residue value.

   The examples for the preventive maintenance operations are; Asphalt crack sealing, Chip sealing, Slurry or micro-surfacing, thin and ultra-thin hot-mix asphalt (HMA) overlay, Concrete joint sealing, diamond grinding, Dowel-bar retrofit, Isolated, partial and/or full-depth concrete repairs to restore the functionality of the slab.

2. **Routine maintenance**: Work that is planned and performed on a routine basis to maintain and preserve the condition of the system and events that restore the system to an adequate level of service. As mentioned, routine maintenance simply entails keeping a close eye on your asphalt and inspecting it for any problems such as cracks, potholes, water damage, or oil stains, and remedying these problems as they occur and before they worsen.

   Cleaning of roadside ditches and structures, Maintenance of pavement markings and crack filling, Pothole patching, Isolated overlays for raveling sections are the basic types of routine maintenance operations

3. **Minor Rehabilitation** - Minor rehabilitation provides non-structural enhancements to the existing pavement and is therefore placed in the category of pavement preservation.

Moreover, Table 2-13 is presented the characteristics of certain pavement preservation activities and what they can provide [116].

Table 2-13: Characteristics of Pavement M&R Activities [116]

Type of Activity	Increase of capacity	Increase of Strength	Reduce Aging Effect	Restore Serviceability
Pavement Reconstruction	×	×	×	×
Major Rehabilitation (Structural Overlay)		×	×	×
Pavement Preservation works				
Minor Rehabilitation			×	×
Preventive Maintenance			×	×
Routine Maintenance				×

Moreover, the timing of the applied treatment types decides whether they are preventive or corrective treatments. Especially in flexible pavements, several common distress types are identified as Rutting, Cracking, Bleeding, Roughness, Weathering, Raveling & pothole [117]. There are several treatment types associates with a particular distress type. Therefore, in such situations, the idea maintenance type shall be select based on the cost-effectiveness and the performance increasing ability. Hicks, et al, (2000) is proposed several preventive maintenance treatments for different distress types as presented in Table 2-14 [117]. Moreover, it further describes the expected pavement life extension.

Table 2-14: Possible Preventive Maintenance Treatments for Various Distress Types [117]

Pavement Distress Type		Crack Sealing	Micro-surfacing	Slurry Seal	Chip Seal	Thin HMA Overlay	Mill or Drind	Spray Injection Patching	Hot Mix Asphalt
Roughness			×			×	×		
Pothole								×	×
Rutting			×			×	×		
Fatigue Cracking* (low severity)			×	×	×	×			
Longitudinal & Transverse Cracking		×	×	×	×	×			
Raveling			×	×	×				
Bleeding			×		×				
Expected Life of Treatment (Years)	Average	3	7	5	5	7	NA	1	3
	Maximum	5	9	7	7	12	NA	3	6

*Preventive maintenance is not applicable for medium to high severity fatigue cracking.
NA – Not Available

However, If the identified distress condition (severity and extend) is related to a structural deficiency and cannot be recovered from preventive maintenance that is not suitable to use preventive maintenance treatment. Therefore, in such situations, either rehabilitation or reconstruction should be considered.

The developing countries have defined their ways of M&R program, especially for local roads. Because of insufficient funding availability, most of the situations have given less attention to the LVRRs. Nepal has defined its maintenance program in several types; routine maintenance, recurrent maintenance, specific maintenance, periodic maintenance & emergency maintenance [118]. Moreover, New road construction, improvement, upgrading, and rehabilitation are not considered to be maintenance activities and they are treated differently. India's rural road maintenance having three different practices; routine maintenance, periodic maintenance & emergency maintenance. Here, Periodic maintenance is considered as a major overhaul of the road typically carried out in a period of 5 to 10 years [119,].

In Sri Lanka, the maintenance program is consisting of routine maintenance, periodic maintenance, reconstruction/rehabilitation, strengthening & road improvement [26]. Moreover, the maintenance activities are categorized under flexible, rigid & gravel based on the pavement type itself.

Further, National Road Master Plan 2018-2027 [26] is described the relevant maintenance practices under each category in each pavement type which are shown in Table 2-15.

Table 2-15: M&R Practices for Each Strategy based on national Road Master Plan 2018 - 2027 [26]

<table>
<tr><th rowspan="2">Pavement Type</th><th colspan="3">Maintenance Type</th></tr>
<tr><th>Routine Maintenance</th><th>Periodic Maintenance</th><th>Reconstruction/Rehabilitation</th></tr>
<tr><td>Flexible</td><td>• Pothole patching
• Crack sealing
• Edge break repair
• Patch sealing
• Patch raveling
• Shoulder repair
• Drain repair
• Vegetation control</td><td>• AC overlay HMA (thickness vary from 40mm-80mm)
• AC overlay PMA (thickness vary from 70mm-125mm)</td><td>• Reconstruction AC overlay HMA (thickness vary from 40mm-100mm)
• Reconstruction AC overlay PMA (thickness vary from 125mm-150mm)</td></tr>
</table>

Rigid	• Pothole patching • Joint sealing • Edge repair • Vegetation control • Drain repair	• Thin bonded overlay • Diamond grinding • Full-depth repair	• Slab replacement & Reconstruction
Gravel	• Gravel priming • Spot graveling • Grading		• Upgrading to SBST or DBST

AC-Asphalt Concrete; HMA-Hot Mix Asphalt; PMA-Polymer Modified Asphalt; SBST-Single Bitumen Surface Treatment; DBST-Double Bitumen Surface Treatment

There are various threshold/ trigger values are defined for new pavement, selection for maintenance, and rehabilitation/reconstruction. The parameters which are used to define these threshold values are in general; distress condition, IRI, structural capacity, etc. Different countries have used various threshold values to identify the road which is a candidate for maintenance. Table 2-16 is presented the various threshold values used globally in selecting M&R activities.

Table 2-16: Recommended M&R Threshold in Worldwide

Reference	**Recommended Maintenance Intervention**		
	Maintenance Type	**Parameter**	**Threshold Value**
Cyprus [121]	Periodic-Thin Overlay for Class-E roads	IRI	3.3m/km
		Deterioration area	16%
	Periodic-Thin Overlay for Class-F roads	IRI	6m/km
		Deterioration area	56%
Spain [41]	Routine Maintenance	IRI	< 6m/km
		Rut Depth	< 25mm
		Macro texture	> 0.6mm
	Surface Restoration	IRI	6-8m/km
		Rut Depth	< 25mm
	Reconstruction	IRI	> 8m/km
		Rut Depth	> 25mm
Taipei City [122]	Minor road maintenance	IRI	> 6.5m/km
Australia[123]	Rehabilitation threshold	IRI	> 6.1m/km
Canada – Ontario [124]	Maintenance threshold for Local roads	IRI	> 3.3m/km

Czech Republic [125]	AC/PCC reconstruction	IRI	> 6.3m/km
Ireland [126]	Maintenance threshold for local roads with AADT<2000veh/day	IRI	> 5m/km
		Rut Depth	> 15mm
Kazakhstan [40]	Maintenance threshold for AC/PCC	IRI	> 3.4m/km
	Maintenance threshold for Crushed stone	IRI	> 4.8m/km
	Maintenance threshold for Gravel	IRI	> 5.6m/km
Lithuania [40]	Maintenance threshold for local roads	IRI	> 4.5m/km
Norway [127]	Maintenance threshold for AC/PCC local roads ADT<1500 veh/day	IRI	> 5m/km
	Maintenance threshold for AC/PCC local roads ADT 1500-5000 veh/day	IRI	> 4.5m/km
New Zealand [128]	Maintenance threshold for local roads	IRI	> 5.71m/km
		Rut Depth	> 20mm
Poland [129]	Reconstruction local roads	IRI	> 6.6m/km
Russia [130]	Maintenance threshold for AC/PCC	IRI	> 4.2m/km
	Maintenance threshold for Crushed stone	IRI	> 7.3m/km
	Maintenance threshold for Gravel	IRI	> 9.3m/km
Slovakia [131]	Reconstruction local roads	IRI	> 8m/km
Sweden [40]	Maintenance threshold for AC local roads ADT<1000veh/day	IRI	> 5.8m/km
Mali, Chile, and Costa Rica [131]	40mm HMA overlay	IRI	> 5m/km
	Reconstruction	IRI	> 8.5m/km
Lisbon, Portugal [132]	Warning level for maintenance	IRI	> 3.5m/km
		Total cracks	> 10%
		Surface disintegration	> 10%
		Rut Depth	> 10mm
Estradas de Portugal [133]	Warning level for maintenance	IRI	> 5.5m/km
		Total cracks	> 20%
		Surface disintegration	> 20%
		Rut Depth	> 20mm

In Sri Lankan practice, intervention criteria for maintenance of pavement depending on several factors. The RDA, Sri Lanka, in 2017 has proposed [134] the trigger values for pavements as; routine, periodic & rehabilitation activities depending on IRI, AADT, v/c ratio, distress condition, etc as shown in Table 2-17.

Table 2-17: Road Maintenance Intervention for National roads with AADT<5000veh/day in Sri Lanka [134]

Pavement Type	**Work Intervention Type**			
	Routine Maintenance	**Periodic Maintenance**	**Strengthening/ Reconstruction**	**Road Improvement/Widening**
Flexible eg: AC, SBST or DBST, PM	IRI ≤ 3.5m/km	IRI 3.5 - 8m/km	IRI > 8m/km	Peak period V/C ratio > 0.8
Unsealed eg: Gravel	Gravel thickness < 100mm & within 3 years routine period	-	-	AADT >3000 veh/day Upgrade to 25mm DBST
				AADT 1000 - 3000 veh/day Upgrade to 15mm SBST
Rigid eg: Concrete	Based on the combination of two parameters 1. Related Surface Distresses (Spalling, Faulting, Rutting and Roughness) 2. The severity of the damage (damaged area %)			

AC – Asphalt Concrete, SBST – Single Bitumen Surface Treatment, DBST – Double Bitumen Surface Treatment, PM – Penetration Macadam, V/C – volume to capacity ratio

Moreover, RDA, Sri Lanka in 2006 has been declared detailed routine and periodic maintenance work standard for LVRRs as shown in Table 2-18 [29]. Five main pavement types are categorized in the work standards.

Table 2-18: Work Standards of RDA for Low Volume Roads [29]

Pavement Type	**Maintenance Type**	**Work Item**	**Intervention Level**
AC	Routine	Crack seal	> 10%
		Pothole patching	> 10 nos/km
		Edge repair	> 50 m^2/km
		Other routine activities	Annually
	Periodic	AC overlay	IRI > 5m/km
CC	Routine	Partial depth repair	Spalling >10%
		Full-depth repair	Damage area > 20%
		Joint sealing	Annually
	Periodic	Slab replacement	Total crack area > 20%

SD	Routine	Crack seal	> 10%
		Pothole patching	> 10 nos/km
		Edge repair	> 50 m^2/km
		Other routine activities	Annually
	Periodic	Resurface	Damage area > 20%
PM	Routine	Pothole patching	> 10 nos/km
		Edge repair	> 50 m^2/km
		Other routine activities	Annually
	Periodic	Sand sealing	Every 5^{th} year
Gravel	Routine	Spot graveling	Gravel thickness < 75mm
		Re-graveling	Gravel thickness < 50mm
	Periodic	Grading	IRI > 12m/km

AC – Asphalt Concrete, CC – Cement Concrete, SD – Surface Dressing, PM – Penetration Macadam

2.7 Multi-objective Optimization Approach

Modern-day design problems in PMS increasing complexity day by day hence disagreeing between objectives has occurred. Several objectives should be optimized in the decision-making process such as minimize total cost, maximize overall condition, maximize reliability, maximize performance, etc. Therefore, objectives are conflicting in and a need for a MOO process shall be adapted to overcome such issues.

Many researchers have proposed several approaches and applications of MOO in PMS. The MOO can be categorized into three methods such as prior articulation of preference, methods with a posterior articulation of preference and interactive methods [136].

The Weighted Sum Method (WSM) is a common approach incorporating preferences in either a prior or a posterior process. This method combines several objective functions into one objective function and defined the optimal solution as one that corresponds to the best value of the weighted sum. The main advantage of this method is its simplified approach to implemented hence several researchers have been used it in their MOO process [137,138]. However, there are several disadvantages produced in this method such as the inability to solve multi-dimensional problems and subjective approach when assigning weightage for objective functions.

Adopting multi-attribute utility theory is another method that is a mathematical framework to analyze choices involving multiple outcomes. The main advantage is its capability to quantify the preferences of decision-makers hence some authors have suggested this method in their studies [106]. Sometimes, it shall be many inputs and preferences that have to be precise then it is difficult to formulate the utility function. The AHP is another method based on obtaining preferences or weights of importance to the alternatives. Here, a pair-wise comparison of alternatives was conducted to estimate criteria weight. This method is effective since it uses a pairwise comparison that allows the decision-maker to compare alternatives relatively. However, it requires complex and time-consuming computation to obtain outcomes in a situation that requires a large number of alternatives this method can be produced biased results.

Furthermore, Artificial intelligence methods such as the use of the GA to solve MOO problems show very interesting results because of their ability to provide good solutions to simple linear optimization problems as well as complex combinatorial problems. Even though this is very effective, it requires relatively higher programming complexity and computation cost. To minimize these issues several researchers are proposed local search heuristics such as 'memetic algorithm' [107], Pareto concept incorporated [136]. Moreover, the 'Pareto optimality concept has increased the accuracy of evolutionary algorithm optimal results searching criteria in MOO hence nowadays many researchers have followed that method in their studies and system development.

The Pareto front concept can be adopted to find the set of optimum solutions which are called non-dominated solutions which have no other solution that can improve at least one of the objectives without degradation of any other objective. Figure 2-13 presented the concept and Pareto-front soring by using a two-objective optimization approach [84].

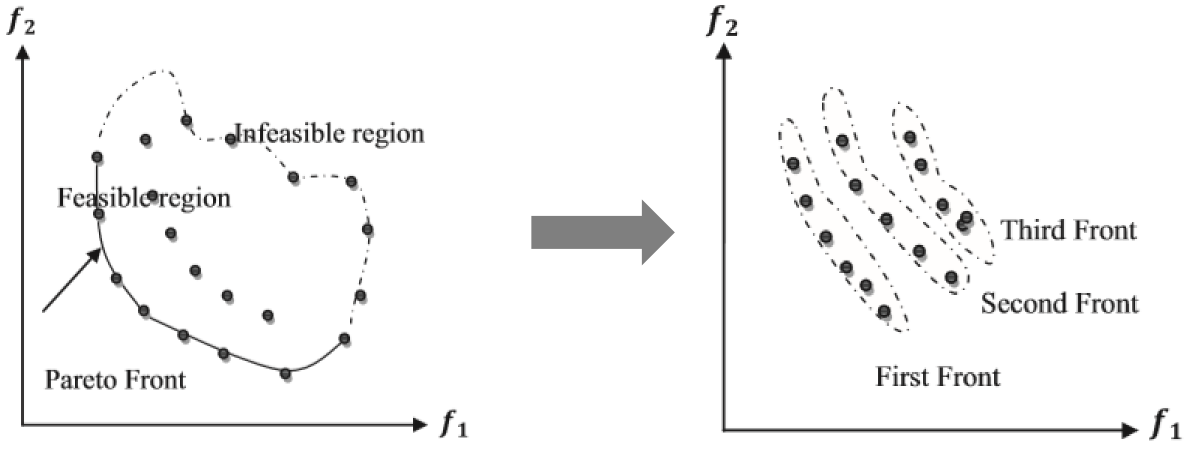

Figure 2-13: Pareto Front Concept and Finding the Optimal Set of Solutions from Bi-Objective Optimization

Mathematically, all the Pareto optimal solutions can be equally acceptable solutions to the multiobjective optimization problem. However, the DM should select the most reliable solution from a Pareto optimal solution set based on his or her judgment or preferences.

Some of the characteristics of the various Multiobjective optimization methods are reviewed and summarized in Table 2-19 [139].

There are several researchers worldwide who have been implemented a multiobjective optimization process in decision-making criteria. Most of them have used maximization of pavement condition or minimization of the total cost as their primary objective function. Moreover, other objectives such as; minimize user cost, maximize the residual value of pavement, minimize system-level travel time, minimize accident cost etc have been commonly used by the researchers. The summary of studies of the most recent addressing the multi-objective problem in PMS is detailed in Table 2-20. Although these studies focused on the MOO problem still relevant constraints should be satisfied. The common attribute of the outcomes found from this research is; it is very efficient and beneficial to the road user, road agency that rather than spend the funding on optimizing a primary objective, several objectives considered at a time is the better option in Engineering point of view.

Table 2-19: Characteristics of Various Multiobjective Optimization Techniques [139]

Technique	Key Characteristics	Advantages	Drawbacks
Weighted Sum Method (WSM)	By assigning positive weights to each objective combines the various objectives into one single objective	• An easy approach, understandable • Compatible with most of the algorithms • Easy to incorporate preferences in either a priori or a posteriori process.	• In the situation of non-convexity may not obtain the Pareto set • A different set of weights may generate the same Pareto front.
Compromise programming	Identified the solutions which are closer to the ideal solution by measuring the distance, The most common approach is the minimization of normalized distance from the ideal solution.	• Easy, understandably procedure and can reduce the Pareto set • Easy to adapt in discrete settings and continuous setting	• Determining the relative importance and the selection of the exponential parameter is the main limitation.
Multiattribute utility theory	An axiomatized mathematical framework for analyzing and quantifying choices involving multiple competing outcomes.	• Can quantify the decision maker's preference • Ability to combine with other optimization methods	• Difficult to construct an individual utility function
Analytical Hierarchical Process (AHP)	Use for the subjective evaluation expressing the relative importance of a set of alternatives	• Can be incorporate the subjective decisions • An understandable and simplified approach to implement	• In the case of many alternatives needs to incorporate the comparison stage would be lengthy and complex to handle.

Table 2-20: The Summary of the Recent Studies Addressing the Multi-Objective Problem in Pavement Management Systems

Reference	Decision Level	Type of M&R Activities	Type of Technique (Solution Algorithm)	Objective Functions
Chikezie, Olowosulu and Abejide (2013) [6]	Network	Crack sealing; Pothole patching, Rehabilitation	GA	1. Max. pavement performance 2. Min. total cost
Santos, Ferreira, and Flintsch (2017) [105]	Network	Cold central plant recycling; Thin hot mix asphalt concrete overlay; Corrective maintenance; Restorative maintenance; Reconstruction.	GA	1. Min. the present value (PV) of the total life cycle highway agency costs 2. Min. the PV of the life cycle road user costs 3. Min. the life cycle greenhouse gas emissions
Fwa, Chan, and Hoque (2000) [140]	Network	Shallow patching; Deep patching; Premix patching; Crack sealing	GA	1. Min. highway agency cost 2. Min. maintenance production 3. Max. network condition level
Chootinan, Chen, Horrocks, and Bolling (2006) [141]	Network	Routine maintenance; Surface treatment; Minor rehabilitation; Major rehabilitation	GA	1. Max. pavement Performance 2. Min. maintenance costs
Meneses and Ferreira (2013) [142]	Network	Non-structural maintenance; Minor rehabilitation; Medium rehabilitation; Major rehabilitation	GA	1. Min. highway agency cost 2. Min. road user cost
Lu and Tolliver (2013) [143]	Network	Minor preservation; seal coat; Crack sealing; Aggregate sealing; Chip seal; Hot mix resurfacing; Hot mill overlay; Reconstruction	GA & Simulated constrained boundary mode	1. Min. pavement network average roughness 2. Min. highway agency cost
Gosse, Smith, and Clarens (2013) [144]	Network	Preventive maintenance: slurry seal; Corrective maintenance; Restorative maintenance; Reconstruction	GA	1. Min. highway agency cost 2. Min. GHG emissions 3. Max. pavement performance
Yu, Gu, Ni, and Guo (2015) [145]	Project	Slurry seal; micro-surfacing; HMA overlay; mill-and-fill; Reconstruction	GA	1. Min. total costs 2. Min. aggregated environmental impacts 3. Max. pavement performance
Torres-Machi, Pellicer, Yepes, and Chamorro (2017) [146]	Network	Fog seal; slurry seal; chip seal; micro surfacing; milling and functional overlay; hot in-place recycling; cold in-place recycling; milling and structural overlay; Reconstruction	Hybrid GRASP	1. Max. Long-term effectiveness of the maintenance program 2. Min. GHG emissions

GA – Genetic Algorithm, HMA – Hot Mix Asphalt, GHG – Green House Gas

2.8 Summary of the Chapter

This chapter identified the relevant parameters, methods and tools needed to develop a PMS and also the practices in LVRRs. First, it was discussed the road management structure and classification in Sri Lanka. It was found that there is no proper system to manage LVRRs due to various issues as limited budget, lack of technical knowledge and data to take decision, etc. Next, a comprehensive review was made on different components in PMS, developed systems in global and best practices for developing countries. From that, it was identified that a simple system with minimum data and a cost-effective reliable pavement condition evaluation method is a primary requirement that was not focused on by the researchers in Sri Lanka.

Next, it was evaluated the parameters and techniques proposed by researchers global to overcome the abovementioned issues. IRI was globally accepted as an effective and efficient pavement condition evaluation parameter while it can capture the distresses significantly. There were several models have been developed to identify the relationship between IRI and distresses, and most of the key distresses such as pothole, raveling, rutting can be captured from the roughness measurement. Various roughness measurement techniques have been used to evaluate pavement condition, while smartphone app-based roughness measurement has been used as a novel technique especially in maintenance planning of network level. Irrespectively the type of smartphone, type of vehicle used still smartphone roughness can be accepted as a reliable method to evaluate the road condition.

Next, it was focused on the development of the decision-making scheme by reviewing the practices worldwide. Most of the developed system's main objective was to maximize the network condition within the given budget level. To support that several decision-making tools were developed such as cost estimation models, decision trees, condition prediction models, etc. In addition to that, this chapter focused on the current practices in the Sri Lankan context by evaluating the relevant maintenance intervention levels, parameters, maintenance strategies, etc.

Further, when there are several objective conflicts with each other the solution solving methods for the multi-objective problem was assessed. The objectives related to safety performance, structural capacity, different cost types were mostly used as the secondary objective functions in MOO models by the researchers. It was identified that Pareto Optimal Concept was more than useful in the assessment. Finally, it was evaluated the problem-solving techniques by reviewing the different optimal solution finding techniques. It was found that linear programming would be easy to use in that manner but when the road network getting larger that is no longer effective. To overcome that most of the researchers had been used GA-based systems due to their ability to find the optimum work program.

3 PAVEMENT CONDITION EVALUATION CRITERIA FOR LOW VOLUME ROADS

The main aim of this chapter is to propose and evaluate a pavement condition evaluation method for LVRRs by considering the cost-effectiveness as well as the accuracy of the measurement. It is proposed to use smartphone-based roughness measurement as the primary condition evaluation parameter alongside the key distress types identified in the pilot study. To achieve these research objectives, the methodology is denoted in the following steps.

1. Established the accuracy of the smartphone roughness measurements which compared with the Bump Integrator IRI.
2. Evaluated the capability of IRI to predict the distress condition on a pavement by developing a relationship between IRI and key distress types.
3. Evaluated the ability of IRI to forecast overall pavement condition, by developing a relationship between PCI (ASTM D 6433-11) and IRI.
4. Evaluated the relationship between IRI vs PSR rating by calculating the model parameters.
5. To forecast the maintenance cost concerning distress level, developed a key distress repair cost estimation model concerning IRI progression.

To carry out the work, a set of data was collected in the pilot study area which is described below.

3.1 Introduction to the Study Area

In this study, LVRRs are defined as roads having ADT of less than 3000 veh/day (based on the Sri Lankan practice and literature study in section 2.3) and those are managed by the local agencies. A road network was selected which consists of 95 road links with a total length of 287.4km, including both single lane and intermediate carriageway lane (width greater than 3.7m as per RDA pavement design manual) [147] limited to a maximum width of 6.2m. All of these roads are belong to local road agencies such as Pradeshiya Sabha, PRDA or municipal council. Moreover, the road inventories of those road links are presented in Table A-1(Appendix A). All the study road segments are bituminous pavement sections while all the roads are in rolling and flat terrain. Moreover, a sample of roads from the LVRR network with different distress levels is shown in Figure 3-2. Further, the summary of road inventories from the selected road network is shown in Table 3-1.

Table 3-1: Summary of Road Inventories in the Road Network

Road type	Number of roads	Average width (m)	Total length (km)
Single-lane roads	68	< 3.7	113.7
Intermediate-lane roads	27	3.7 – 6.2	173.7
Total	95	-	287.4

Figure 3-1: Example of Road Sections with Different Distress Levels in The Low Volume Rural Road Network

ADT values from 15-minute interval flow counts were extracted from the database of RDA, Sri Lanka under the Integrated Road Investment Program (iRoad) project. The traffic was classified by vehicle type into 6 categories: namely, Motorcycle (MC), Three-Wheeler (TW), Car/ Van, Light Good Vehicles (LGV), Heavy Vehicles (HV) & Others. A total of over 94,000 vehicles were categorized during the study. The vehicle composition observed during the survey is shown in Figure 3-2. The dominant vehicle category was the MC with a share of 67%. Overall, 88% of the traffic stream was made up of small vehicles (MC and TW). The percentage of passenger cars/vans, light good vehicles, HVs as low as 5%, 3%, 3% respectively. Other vehicles category comprised majority with tractors. This shows the heterogeneity of the traffic stream in LVRRs and is significantly different from the composition observed in national roads.

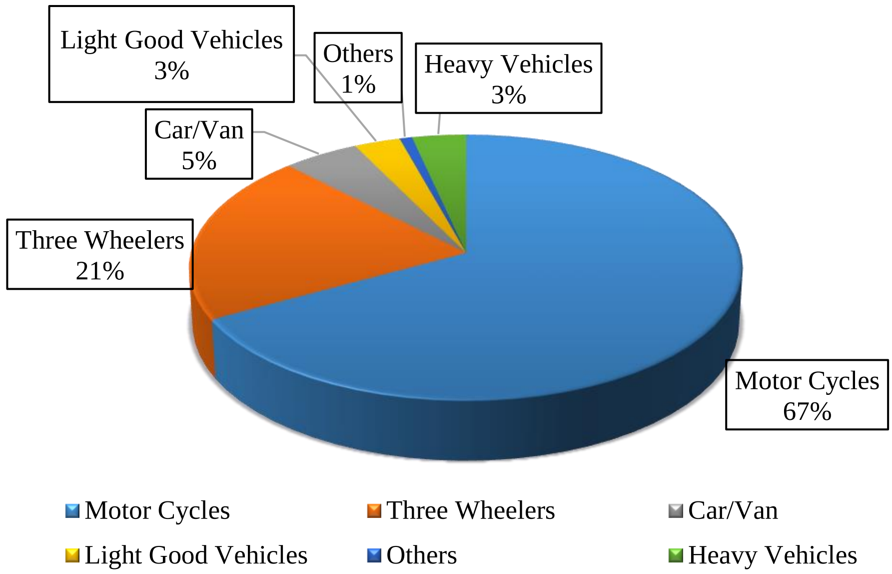

Figure 3-2: Vehicle Distribution of the Road Network

Moreover, the summary of traffic characteristics in the road network is shown in Table 3-2. Moreover, the cumulative distribution of the traffic volume in the network is presented in Figure 3-3.

Table 3-2: Summary of Traffic Characteristic in the Rural Road Network

Traffic volume (ADT)	Mean (μ)	912 veh/day
Percentage of roads	<500 veh/day	32%
	500-1500 veh/day	41%
	>1500 veh/day	27%

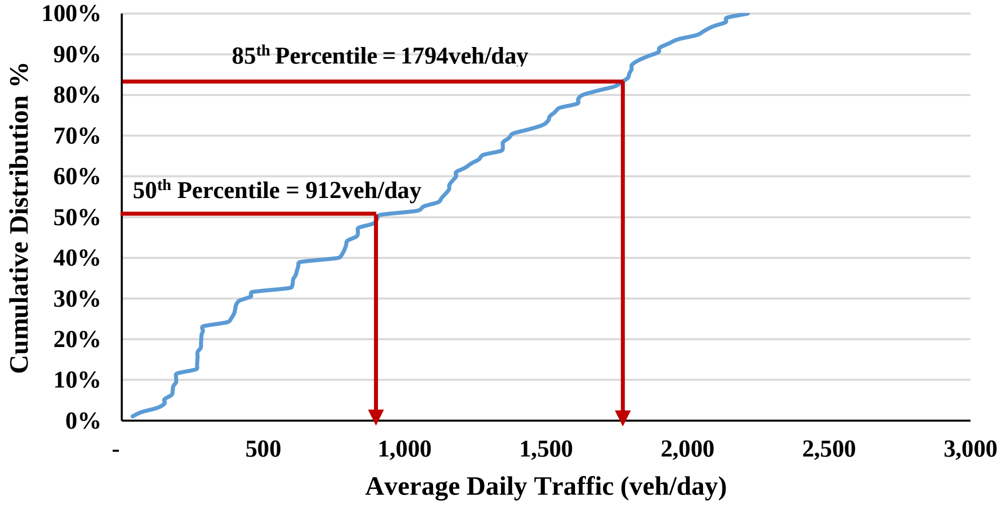

Figure 3-3: Cumulative Distribution of the Traffic Volume in the Network

3.2 Relationship between Bump Integrator IRI and Smartphone-based Roughness Measurement

3.2.1 Data Collection

The validity of smartphone-based roughness measurement is evaluated by comparing with pavement roughness measured by Bump Integrator (Class III type) [84] which is calibrated through the Z-250 walking profilometer.

A length of 1 kilometer was selected for each segment to obtain a reasonable number of samples, whereas the IRI was calculated for each 100-meter long segment then averaged for 1 kilometer. There are three reasons for the selection of this minimum length of a segment:

1) In general, a PMS uses sections 100 m long or more.
2) The length reduction of these segments could increase errors during the cross-matching between data collected by Roadroid and through Bump Integrator.
3) ASTM recommended that IRI be calculated under a minimum distance of 160 m (0.1 mi) [148].

In addition to that, when selecting the segments, the locations where bridges are located, any congested area due to community activities have taken place were omitted to ensure the consistency of the measurement.

Roadroid runs and Bump Integrator roughness measurements were both performed using a passenger car. Before use Bump Integrator IRI, it was calibrated for vehicle speed, suspension effect, tire pressure, etc. Table A-2 (Appendix A) shows the calibration sheet which is used to obtain the IRI value while Figure A-1 (Appendix A) presented the calibration graph for different speed levels. Finally, the output from the Bump Integrator IRI was extracted for each 100 m segment as shown in Figure 3-4.

	A	B	C	D	E	F	G	H	I	J
1	CHAINAGE	LRP_FROM	LRP_TO	LRP_NUM	SPEED	RAW_C_1	RAW_C_2	RAW_C_1	RAW_C_2	C_ROUGH
2	100	0	100	0	46	1104	0	11039	0	3.83
3	200	100	200	0	48	893	0	8919	0	3.58
4	300	200	300	0	48	838	0	8377	0	3.52
5	400	300	400	0	48	812	0	8092	0	3.49
6	500	400	500	0	35	1060	0	10578	0	3.78
7	600	500	600	0	6	1832	0	18296	0	4.67
8	700	600	700	0	27	1708	0	17020	0	4.52
9	800	700	800	0	38	1328	0	13232	0	4.08
10	900	800	900	0	43	1142	0	11385	0	3.87
11	1000	900	1000	0	42	1335	0	13330	0	4.1

Figure 3-4: Example of the Output IRI values from Bump Integrator

Roadroid mobile application (version 2.4.1) [149] was used in data collection [150] using a tri-axial accelerometer embedded in a Huawei GR5 with an Android operation system. The results are given in two forms such as estimated IRI (eIRI) and calculated IRI (cIRI), both are an estimate of the value of the IRI defined by the ASTM E1926-98 standard [75]. eIRI value is derived based on peak and RMS vibration analysis at a speed range of 20-100 km/hr and cIRI is derived on quarter car simulation at the speed range of 60-80 km/hr [30]. In the study, a roughness survey is conducted in a speed range of 30-40 km/hr, therefore eIRI values were selected as the output. At the time of Roadroid runs performed the smartphone was mounted on the windshield of the car. If the car is moving above or below the specified speed ranges (20km/hr – 100km/hr) of Roadroid estimated IRI, the phone beeps and no measurements are recorded at that speed.

After data was collected to the smartphone those were uploaded to the Roadroid website and downloaded the aggregate files which are generated as shape & KML files as shown in Table A-3 (Appendix A).

The total number of 76 road segments in the LVRR network were selected and the measured IRI values were obtained using the described procedure. The roughness values obtained from both methods are presented in Table A-4 (Appendix A).

3.2.2 Establishing Relationship between Bump Integrator IRI vs Roadroid IRI

The two IRI measurements were compared by fitting a correlation. Figure 3-5 shows the relationship between IRI values from Bump Integrator and eIRI values from the Roadroid app. It is observed that Roadroid slightly underestimates the IRI measurements compared to the

Bump Integrator IRI. However, the applicability of eIRI with Bump Integrator IRI was confirmed by a regression model which is given in Equation 11, with an R-squared (R^2) of 0.71 and the p-value of 0.001 under 5% significance level.

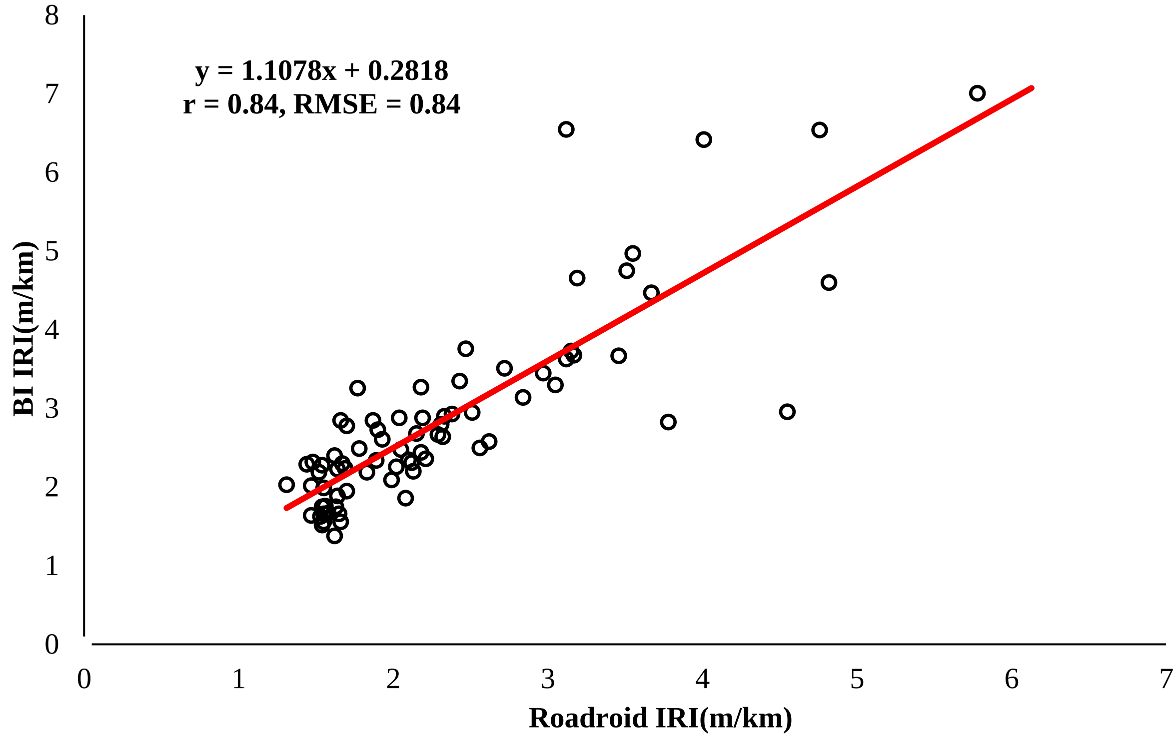

Figure 3-5: Comparison between Bump Integrator IRI vs Roadroid IRI

$$\mathrm{IRI_{BI}} = 1.1078\mathrm{IRI_{Roadroid}} + 0.2818 \quad (11)$$

Where, IRI_{BI} is the roughness value measured by Bump Integrator in-unit m/km; $IRI_{Roadroid}$ is the eIRI value measured by Roadroid app in-unit m/km

Moreover, the statistical summary of the fitted regression line is illustrated in Table 3-3 & 3-4.

Table 3-3: Summary of Statistical Analysis of Fitted Line between Roadroid IRI and Bump Integrator IRI

Regression Statistics	
Multiple R	0.84
R-Squared	0.71
Standard Error	0.66
Observations	76

Table 3-4: ANOVA Table of the Model

Source of Variability	***df***	***SS***	***MS***	***F***	***Significance F***
Regression	1	76.882	76.882	178.144	0.000
Residual	74	31.936	0.432	-	-
Total	75	108.818	-	-	-

From Figure 3-7, It can be observed that in low roughness values, both IRI measurements are clustered with a narrow range, while when the roughness value is increased more variation was observed. Although Roadroid slightly underestimates the roughness measurements; and when its values were compared to that of the standard profiler, the difference is statistically significant. However, road agencies with tight budgets can integrate Roadroid instead of their subjective pavement condition surveys on LVRRs which would provide ride quality measurements with less human influence and make a reasonable decision for pavement sections requiring treatment.

3.3 Relationship between IRI and Pavement Distress Condition

95 records of distressed pavement data, from the selected LVRRs, are collected simultaneously with the IRI as presented in Table A-1 (Appendix A). Six key distresses that are prevalent in LVRRs have been identified during the field investigation, namely, pothole (POT), raveling (RAV), cracking (CRA), patches (PAT), edge gap (EDG) and edge break (EDB).

Table 3-5 shows that the categorization of the identified surface distress in the data collection is grouped into three basic causes: Load, climate, and other. It is known that load-induced distress is caused by dynamic loads transmitted from the vehicle, while climate-induced distress is caused by environmental effects such as rainfall and temperature fluctuations during certain periods.

Moreover, construction errors, design errors, damages by solvents and equipment used, the effect of environmental organic origin (tree leaves, etc.), and damage caused by vehicle operation (fire, leaks, etc.) can be recognized as other causes of distress [151].

Table 3-5: Distress Classifications for Asphalt Concrete Pavement in ASTM D 6433-11

Distress No.	Distress Type	Unit of Measure	Reason to propagate distress
01	Raveling	m^2	Climate
02	Pothole	m^2	Load/Other
03	Cracking	m^2	Load/Climate
04	Edge Gap	m	Other
05	Edge Breaking	m^2	Load
06	Patching	m^2	Other

The Pearson correlation analysis was conducted to find the relationship between IRI and each distress type separately. Three types of regression functions were tested; linear, quadratic non-linear and logarithm non-linear and the best representative function is selected by statistical analysis. The test values of the correlation coefficient (r), hypothesis and analysis of variance (ANOVA) were used to select the best-fitted function.

3.3.1 IRI vs Raveling

Figure 3-8 illustrated the graph showing the relationship between IRI and raveling density. The raveling was observed from 32 pavement sections. The graph shown in Figure 3-6 indicates a positive relationship between raveling and IRI. As shown in Figure 1, raveling distress is propagated beyond IRI of 3 m/km which indicates even in a relatively new pavement section raveling can be seen due to the climate effects. The Pearson correlation indicates that about 61% of the IRI and raveling density observations were described by the non-linear function. The best model formula was identified as the logarithmic function: IRI = 5.43 + 1.24 ln (RAV). In the hypothesis test, the p-value was found to be 0.001, which provided that there is a significant relationship between IRI and raveling density at a 95% confidence level.

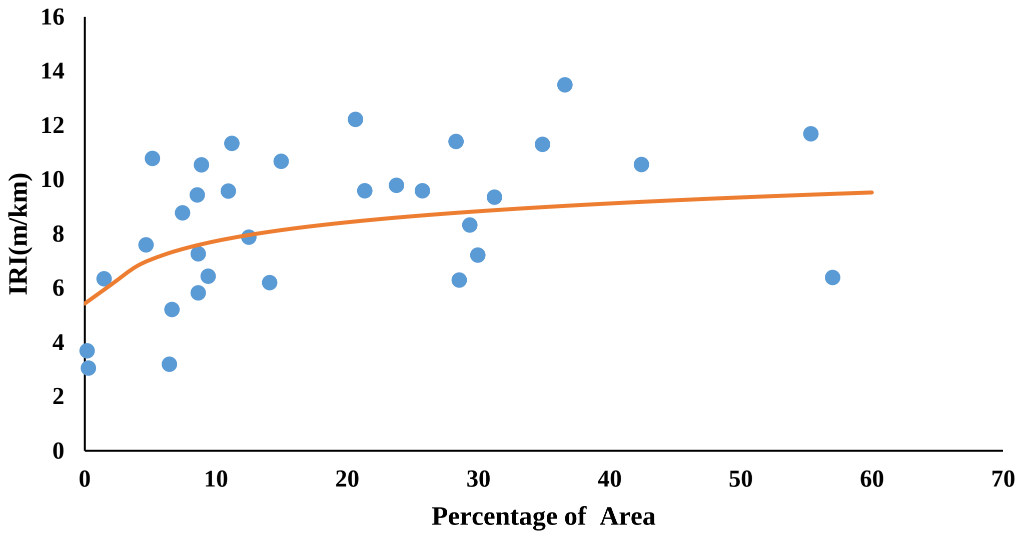

Figure 3-6: Plot of IRI vs Raveling Density

3.3.2 IRI vs Pothole

Figure 3-7 presented the graph showing the relationship between IRI and pothole density. The pothole was observed in 12 different pavement sections. The graph shown in Figure 3-9 indicates a positive relationship between pothole progression and IRI. The maximum pothole density observed was 0.44 % (equivalent to 28 potholes per kilometer). As shown in Figure 3-9, pothole distress was propagated beyond IRI of 7m/km which indicated potholes are generally observed in older pavement segments. The correlation coefficient indicates that about 55% of the IRI and pothole density were described by the non-linear relationship. The best formula was the logarithmic function: IRI = 12.62 + 0.97 ln (POT). In the hypothesis test, the p-value was found as 0.021, which indicated that there is a good relationship at a 95% confidence level.

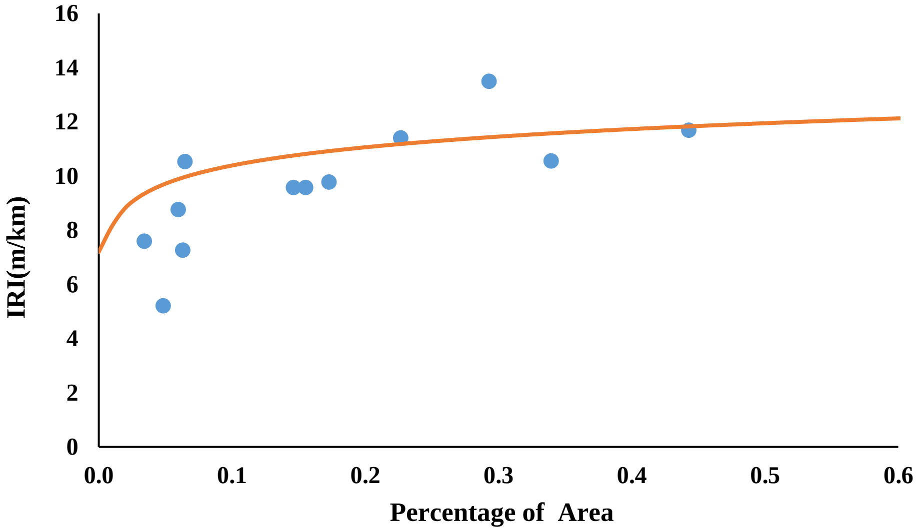

Figure 3-7: Plot of IRI vs Pothole Density

3.3.3 IRI vs Edge Breaking

Pavement edge breaking is defined as the edge cracks or edge break is observed within 500mm from the pavement edge. The effect of edge breaking on IRI only valid for the narrow roads hence the relationship was established only for the narrow roads which are having average road width less than 3.7m (single lane roads as per RDA classification) [147]. Figure 3-10 illustrated the graph showing the relationship between IRI and edge-breaking density. The edge breaking was observed in 36 pavement sections. The maximum edge-breaking density observed was 12 %. As in Figure 3-8, edge breaking was mostly seen in between roads with IRI 2.5 – 6 m/km. The value of the correlation factor indicates that about 56% of data was described by the linear function: IRI = 1.97 + 0.48 EDB. In the hypothesis test, the p-value was found to be 0.001, which indicates a good relationship in 95% confidence level.

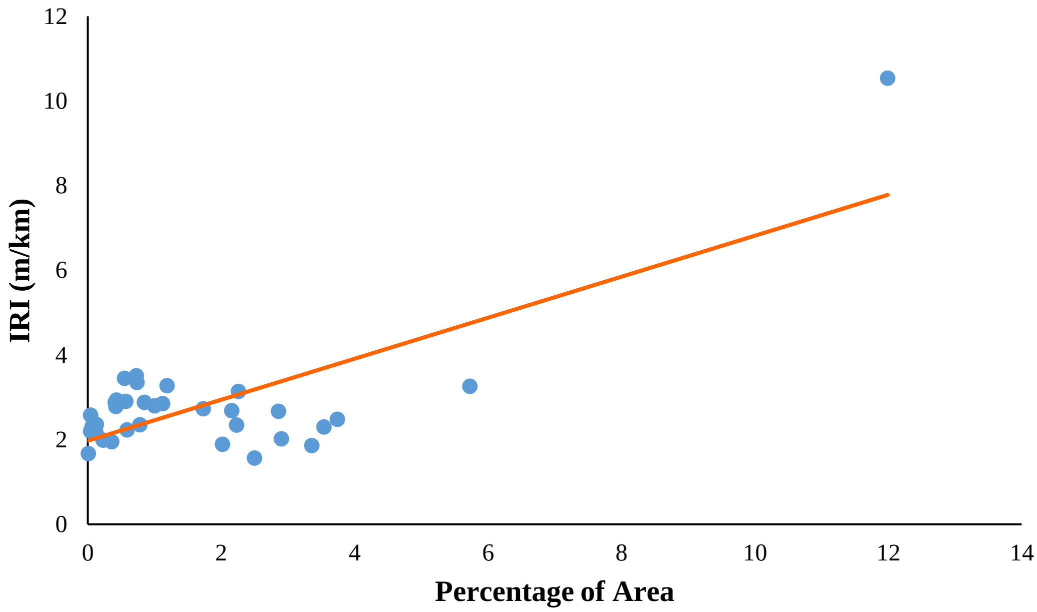

Figure 3-8: Plot of IRI vs Edge Breaking Density for Narrow Roads

3.3.4 IRI vs Edge Gap

The edge gap length was calculated by measuring linear length along both sides of a pavement section which exceeds the gap between carriageway and shoulder more than 10cm. Since most of the LVRs are narrow in width, in a situation where two vehicles traveling opposite directions pavement edges have to be used. Therefore, edge gaps are propagated as observed in 15 pavement sections of this network. As per the edge breaking, edge gap is also significant only in narrow road sections. Figure 3-9 shows the relationship between IRI and edge gap, which indicated a positive relationship. The maximum edge gap observed was 14%. The correlation factor indicated that about 52% of the data were described by the logarithmic function: IRI = 8.84 + 0.78 ln (EDG). In the hypothesis test, the p-value was found to be 0.049, which indicates that there is marginal evidence at a 95% confidence level of the relationship between IRI and edge gap.

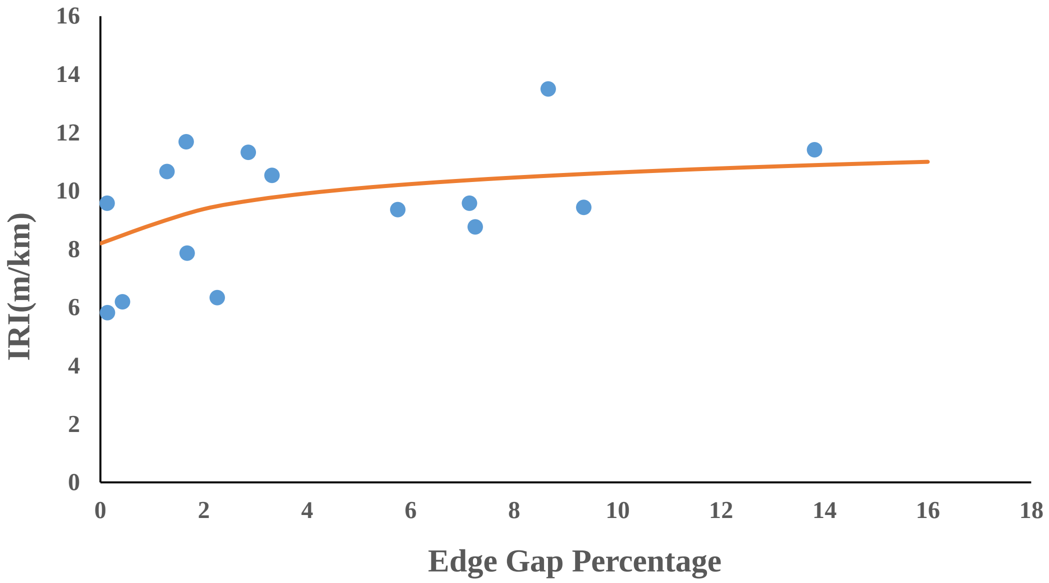

Figure 3-9: Plot of IRI vs Edge Gap Percentage

The other two distress types; cracking & patching were also recorded in terms of the percentage surface area affected by the distress. Moreover, the boundary area surrounding the crack was measured and defined as the affected area. The analysis was repeated following the abovementioned steps and found that relatively lesser correlation between IRI; 34% for cracking and 11% for patching. Moreover, the best-fitted models and graphical representations are illustrated in Table 3-6 & Figure 3-9.

The observed IRI values were in the range of 1.38m/km to 13.5m/km. Furthermore, most of the distress progression was identified to take place beyond IRI of 3m/km. Raveling is the most common distress type, in the new pavement, as well as older ones with IRI, are ranges from 3m/km to 13m/km. In addition to that, road sections with potholes are likely to be older pavements with IRI greater than 6m/km. Further, the road segments which shown edge breaks are likely to represent roads with good IRI. However, cracking and patching did not show a good relationship with IRI progression.

The summary of the best-fitted functions is shown in Figure 3-10, and the statistical results were illustrated in Table 3-6.

Table 3-6: Summary of IRI vs Distress Density Functions

Distress types	Number of Roads with Distress (N)	Maximum Observed Density (%)	Correlation (r)	Best fitted function	P-value
RAV	32	57	0.61	IRI=5.43 + 1.24 ln (RAV)	0.001
POT	12	0.44	0.55	IRI=12.62 + 0.97 ln (POT)	0.021
EDB	36	12	0.56	IRI=1.97 + 0.48 (EDB)	0.001
EDG	15	14	0.52	IRI=8.84 + 0.78 ln (EDG)	0.049
CRA	35	17	0.34	IRI=6.08 + 0.29 (CRA)	0.048
PAT	25	5	0.11	IRI=8.41 + 0.17 ln (PAT)	0.616

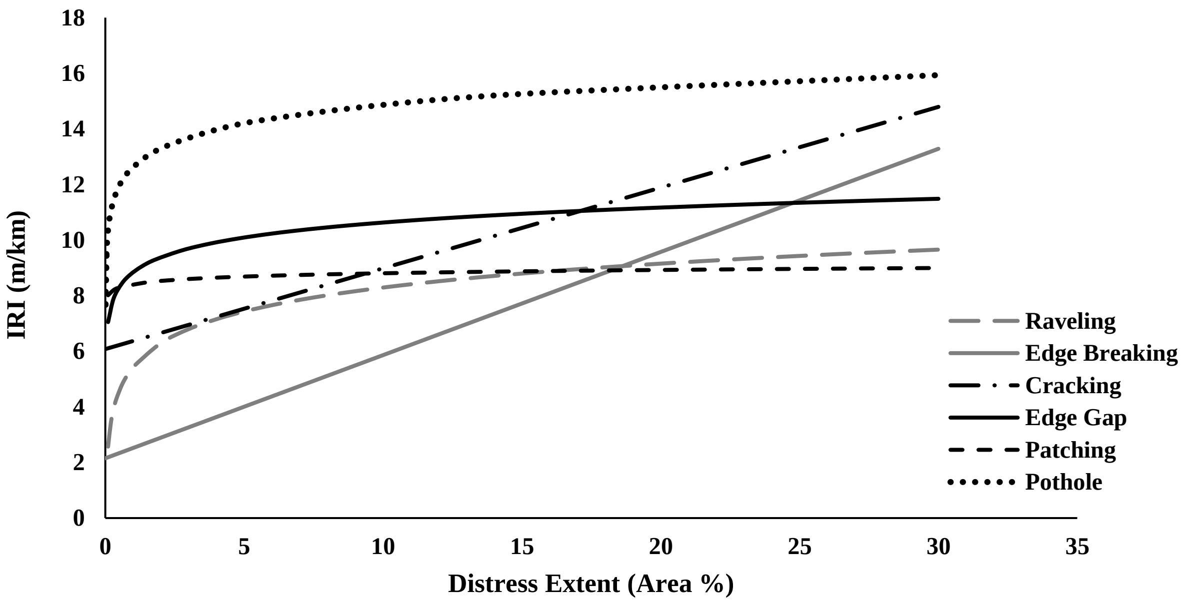

Figure 3-10: Best Fitted Functions between IRI vs Distress Density

3.4 Multiple Regression Analysis between IRI vs All Distress Types

Most of the road segments contain more than one distress type, therefore it should be evaluated the effect of combined distress on IRI. For that, a multiple regression model was developed to assess the relationship between IRI and distresses for all stages of pavement life. All six distress types were used and by using the stepwise multiple linear regression analysis techniques significant distress types were identified. In the analysis, backward elimination criteria were used in the stepwise regression analysis.

The linear regression model is in the form:

$$IRI = a_0 + a_1RAV + a_2POT + a_3EDB + a_4EDG + a_5CRA + a_6PAT$$

Where a_0, a_1, a_2,……, a_6 are the regression coefficient

RAV – Raveling distress density, POT – Pothole distress density, EDB – Edge breaking distress density, EDG – Edge gap distress density, CRA – Cracking distress density & PAT – Patching distress density

Except for edge gap distress, all other distress densities are in form of area percentage and for edge gap, linear length percentage was used.

As the first step, it was verified whether there are highly correlated independent variables. It was found that there are no highly correlated ($r > 0.8$) independent variables as per the correlation matrix in Table 3-7.

Table 3-7: Correlation Matrix of Independent Variables (Distress)

	POT	**RAV**	**CRA**	**EDG**	**PAT**	**EDG**
POT	1	-	-	-	-	-
RAV	0.63	1	-	-	-	-
CRA	0.31	0.29	1	-	-	-
EDG	0.44	0.36	0.25	1	-	-
PAT	0.38	0.40	0.45	0.40	1	-
EDB	-0.07	-0.19	-0.00	-0.03	-0.11	1

Then the elimination process is performed by starting with all independent variables, testing the deletion of each variable using the model fit criterion; p-value < 0.05. Deleting the variable (if any) whose loss given the most statistically insignificant deterioration of the model fit. This process was repeated until no further variables can be deleted without a statistically insignificant loss of fit.

Since edge breaking and edge gap has effect to the IRI only in narrow roads, the multiple regression models were plotted for two categories based on the stratified sampling. The two road groups are referring as narrow roads (average width less than 3.7m) and wider roads (average width greater than or equal to 3.7m). In narrow roads all the distress types are included in the analysis while in wider roads edge breaking and edge gap distresses are not considered.

3.4.1 Multiple Regression Model between IRI vs Distresses for Narrow Roads

Patching distress is removed in elimination process based on the model fit criterion. The distresses that showed a significant relationship to the IRI index included Pothole (POT), Raveling (RAV), Cracking (CRA), Edge Gap (EDG) and Edge Breaking (EDB). The regression model developed is as in Equation 12:

$$\mathrm{IRI} = 2.30 + 9.62\mathrm{POT} + 0.09\mathrm{RAV} + 0.34\mathrm{CRA} + 0.59\mathrm{EDG} + 0.16\mathrm{EDB} \qquad (12)$$

Table 3-8: Statistical Summary of the Multiple Regression Model for Narrow Roads

Regression Statistics	
Multiple R	0.94
R Square	0.86
Standard Error	1.10
Observations	61

Table 3-9: ANOVA Table of the Multiple Regression Model for Narrow Roads

Parameter	***Df***	***SS***	***MS***	***F***	***Significance F***
Regression	5	741.810	247.270	77.426	0.000
Residual	56	290.621	3.194		
Total	61	1032.431			

Predictor	***Coefficients***	***Standard Error***	***t Stat***	***P-value***
Constant	2.30	0.2129	13.63	0.000
POT	9.62	0.0312	9.55	0.000
RAV	0.09	0.0162	9.55	0.000
CRA	0.34	0.0677	4.32	0.000
EDG	0.59	0.0891	4.49	0.000
EDB	0.16	0.047	4.67	0.000

The p-values for all variables are close to zero, indicating a significant statistical relationship between the distress types and the predicted values of IRI (Table 3-8 & 3-9). However, the p-value of patching distress is greater than 0.05, hence omitted in the stepwise analysis. Therefore, there is enough evidence to exclude the patching. The data reflect the dependency between IRI and types of distress. The coefficient of multiple determinations (R^2) was 86%, which represents that 86 percent of the IRI value is explained by the regression model.

Multicollinearity symptoms exist when there is a strong linear relationship or correlation between one or more of the independent variables. Variation Inflation Factor (VIF) can be used as a parameter to identify the degree of multicollinearity. Mathematically, the VIF value for the multiple regression model is equal to the ratio of the overall model variance to the variance of the model that includes only that single independent variable. The mathematical expression for calculating VIF is shown in Equation 13.

$$\mathrm{VIF} = \frac{\mathrm{SE}^2\,(n-1)\,\sigma^2}{\mathrm{OSE}^2} \tag{13}$$

Where, SE – Standard error of the individual variable, n – Number of observation, σ – Standard deviation, OSE – Overall standard error

A rule of thumb for interpreting the VIF to define by Concise Encyclopedia of Statistics as follows [153];

- VIF = 1; Not correlated
- 1 < VIF < 5; Moderately correlated
- VIF ≥ 5; Highly correlated

Therefore, all the distress types in this model are moderately correlated as VIF values presented in Table 3-10. That provides sufficient evidence that there are no multicollinearity symptoms.

Table 3-10: VIF values of the Multiple Regression Model for Narrow Roads

Distress Types	Variance Inflation Factor (VIF)
POT	1.10
RAV	1.25
CRA	1.21
EDG	1.18
EDB	1.12

Further, the regression model is validated for narrow roads by using 32 road segments as presented in Table A-5 (Appendix A). It was found that good estimation for the regression model with the Mean Absolute Percentage Error (MAPE) is 11.3% with the correlation factor 0.88 (Figure 3-11).

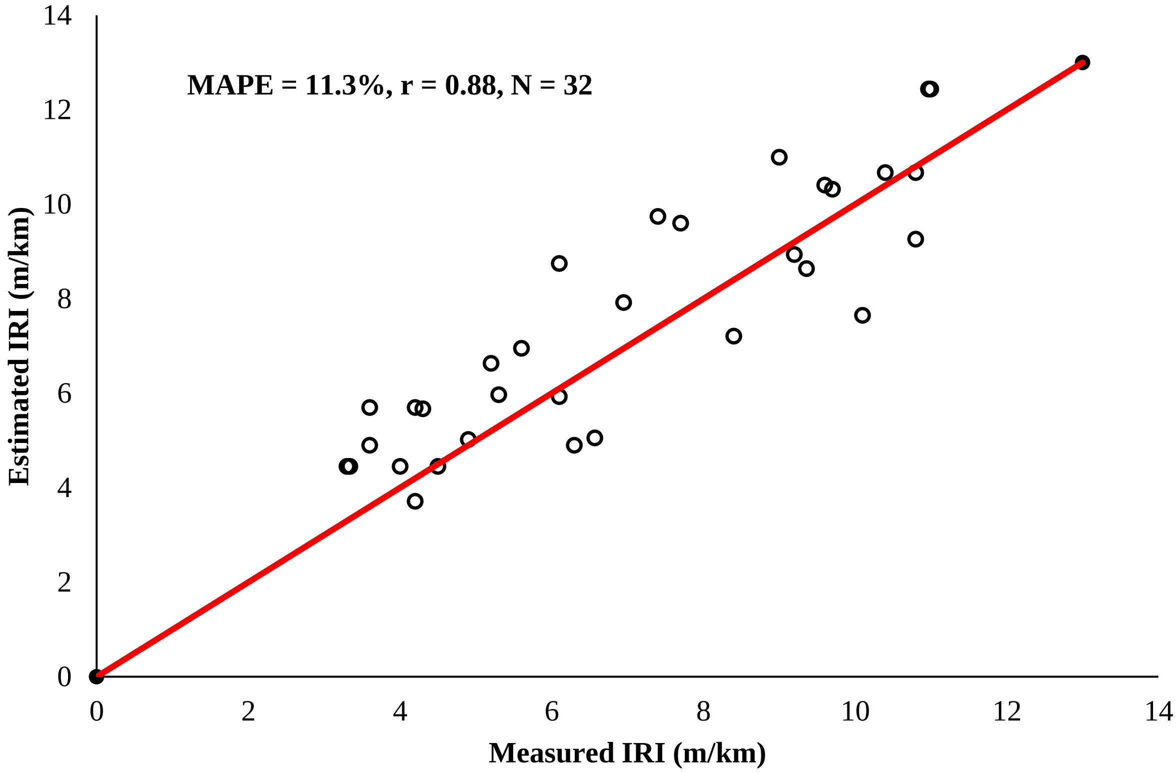

Figure 3-11: Regression Model Validation for Narrow Roads

3.4.2 Multiple Regression Model between IRI vs Distresses for Wider Roads

Edge breaking (EDB) & Edge gap (EDG) were excluded in wider roads since the contribution from edge failures for wider roads is not significant as in narrow roads. The same approach backward elimination stepwise multiple regression techniques were used for this model.

Table 3-11 & 3-12 illustrated the results of multiple regression analysis. The distresses that showed a significant relationship to the IRI index included Pothole (POT), Raveling (RAV), Cracks distress (CRA), and Patching (PAT). The regression model developed is as in Equation 14:

$$\mathrm{IRI} = 2.85 + 11.36\mathrm{POT} + 0.16\mathrm{RAV} + 0.08\mathrm{CRA} - 0.49\mathrm{PAT} \tag{14}$$

Table 3-11: Statistical Summary of the Multiple Regression Model for Wider Roads

Regression Statistics	
Multiple R	0.93
R Squared	0.86
Standard Error	1.31
Observations	27

Table 3-12: ANOVA Table of the Multiple Regression Model for Wider Roads

Parameter	***Df***	***SS***	***MS***	***F***	***Significance F***
Regression	4	48.186	12.047	14.164	0.002
Residual	23	5.953	0.850		
Total	27	54.140			

Predictor	***Coefficients***	***Standard Error***	***t Stat***	***P-value***
Constant	2.85	0.534	11.821	0.000
POT	11.36	2.278	5.693	0.000
RAV	0.16	0.062	3.627	0.003
CRA	0.08	0.068	3.336	0.012
PAT	-0.49	0.226	-2.449	0.044

The p-values for all parameters are close to zero, indicating a significant relationship between the distress types and the predicted values of IRI. The data reflect shown that the dependency between IRI and types of distress in relatively older pavements after pothole progression. The coefficient of multiple determinations (R^2) equals 86%, which means that 86 percent of the IRI value were represented and explained by the regression model. It also indicated that potholes as the key distress type in wider roads as well as the narrow roads sections and with the increasing of the pothole, IRI would be rapidly increased. Moreover, an important observation was made such that the excess of patching sections, roughness would be reduced significantly. That characteristic was identified from the negative regression coefficient value (- 0.49) for patching.

Moreover, all the distress types in this model were moderately correlated as the VIF values presented in Table 3-13. That provides sufficient evidence that there are no multicollinearity symptoms.

Table 3-13: VIF values of the Multiple Regression Model for Wider Roads

Distress Types (Wider Roads)	P-value	Variance Inflation Factor (VIF)
Pothole	0.000	1.16
Raveling	0.003	1.21
Cracking	0.012	1.57
Patching	0.044	1.68

3.5 The Relationship between IRI vs PCI

The PCI index was calculated by following the ASTM D 6433-11 standard for the roads having detailed distress data included type and extend [26]. In calculating the PCI, deduct value for moderate severity condition was used and based on the density, the PCI calculation process was conducted. All 95 road segments were used in the analysis while calculated PCI values alongside the respective IRI are presented in Table A-1. Linear and non-linear regression analysis methods were used to find the best-fitted function between IRI and PCI.

It was found that calculated PCI has a strong relationship with IRI for the selected road network as shown in Figures 3-12. The relationship was developed with a range of IRI from 1.38 m/km to 13.5 m/km and the calculated PCI value varies from 9 to 100. The sigmoidal function has represented the best-fitted function with an adjusted coefficient of determination (R^2) 0.75 for IRI with PCI and shown in Equation 15. The statistical summary of the model is presented in Table 3-14.

$$\mathrm{IRI} = \frac{10.98}{1+\left(\frac{\mathrm{PCI}}{65.9}\right)^{4.27}} \tag{15}$$

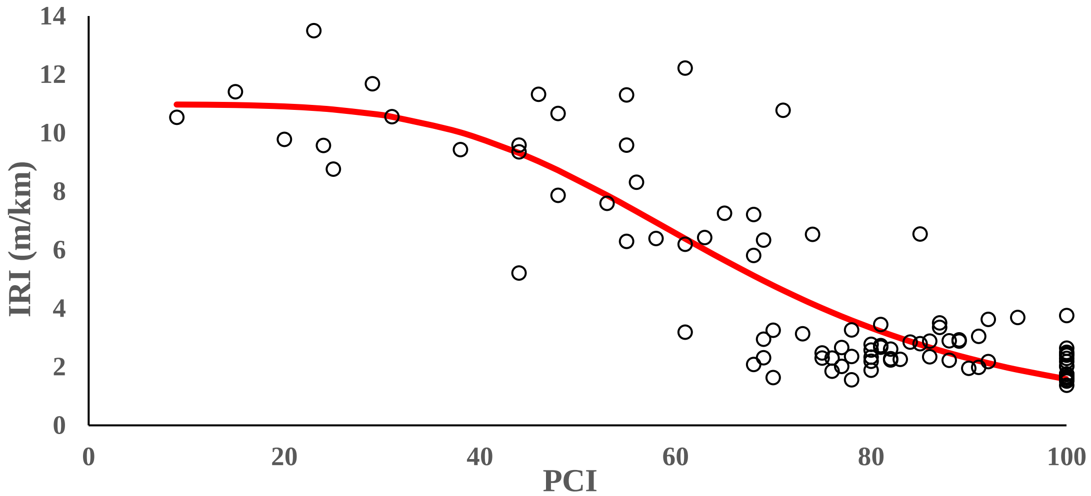

Figure 3-12: Relationship between IRI and PCI

Table 3-14: Statistical Summary of the IRI vs PCI Model

Regression Statistics	
Multiple R	0.87
R-Squared	0.75
Standard Error	1.66
Observations	95

Parameter	***Df***	***SS***	***MS***	***F***	***Significance F***
Regression	1	775.735	775.735	281.047	7.42E-30
Residual	93	256.695	2.760		
Total	94	1032.431			

Furthermore, categorization was conducted for selected road sections based on the defined IRI and PCI ranges. National Road Master Plan, RDA, Sri Lanka had been declared the road distribution based on IRI as; Excellent: IRI < 3 m/km, Good: IRI 3 – 5.5 m/km, Fair: IRI 5.5 – 7 m/km, Poor: IRI 7 – 10 m/km, Bad: IRI > 10 m/km [87].

Moreover, ASTM D5340 defines PCI categories as; Good: 100-85, Satisfactory: 85-70, Fair: 70-55, Poor: 55-40, Very Poor: < 40 [152]

Based on the abovementioned threshold values, respective IRI & PCI ranges are defined as shown in Table 3-15. Then, categorization of roads is done based on each basis and found the similarity concerning each index. In the comparison, the road sections in the PCI range are matched with the appropriate IRI range with an IRI tolerance of ±0.5 m/km. The reason to allocate a tolerance was that there can be an error in measuring roughness due to various human and equipment factors. Also, the change of IRI in 0.5m/km can be acceptable in the measurement procedure.

A similarity index as a percentage was developed based on the categorization shown in Table 3-14. Out of 95 road sections selected from the network, 69 road sections shown similarity in both condition measurement methods. The road segments in the middle range shown the least similarity (54%) while upper and lower ranges were shown a relatively higher similarity index (88% in the Good category & 94% in the Poor category). These results provide strong evidence about the applicability of IRI as a condition measurement parameter for the LVRR network-level maintenance planning.

Table 3-15: Categorization of Pavements In terms of IRI and PCI

<table>
<tr><th>Category of condition</th><th colspan="2">IRI range (m/km) [87]</th><th>PCI range [152]</th></tr>
<tr><td>Good</td><td colspan="2"><3</td><td>85-100</td></tr>
<tr><td>Fair</td><td colspan="2">3-7</td><td>55-85</td></tr>
<tr><td>Poor</td><td colspan="2">>7</td><td><55</td></tr>
<tr><th colspan="4">Similarity Index</th></tr>
<tr><th>Category</th><th>Number of roads in PCI range</th><th>Number of roads in similar IRI range</th><th>Similarity Index</th></tr>
<tr><td>Good</td><td>34</td><td>30</td><td>88%</td></tr>
<tr><td>Fair</td><td>45</td><td>24</td><td>54%</td></tr>
<tr><td>Poor</td><td>16</td><td>15</td><td>94%</td></tr>
<tr><td>Overall Similarity Index</td><td>95</td><td>69</td><td>73%</td></tr>
</table>

Based on the results, it can be established that roughness values represent a similar assessment that would be made by evaluating the distress condition of a pavement. Therefore, roughness information can be obtained at a lower cost and in less time would provide a reliable metric to evaluate the road condition especially for network-level condition evaluation in rural roads.

Furthermore, Spearman's rank correlation coefficient (r_s) was calculated between IRI and PCI to evaluate the similarity of two indices used in road prioritization. The Spearman correlation coefficient (r_s), can take values from +1 to -1. The r_s of +1 indicates a perfect association of ranks, the r_s of zero indicates no association between ranks and the r_s of -1 indicates a perfect negative association of ranks.

The road prioritization concerning both indices is illustrated in Table A-6 (Appendix A). It is referred to the most priority road as rank 1 and the least priority road is referred to as rank 95 (total number of road segments). As the calculations Spearman's rank correlation coefficient (r_s) of 0.72. This indicates a strong positive relationship between the ranks separately obtained in IRI prioritization and PCI prioritization. That is, the higher the rank in the IRI perspective, the higher ranked in PCI would be obtained and vice versa. That suggests that a strong relationship/ similarity between two indices in prioritization of the roads.

3.6 The Relationship between IRI vs PSR

The Present Serviceability Rating (PSR) is based on an Engineer's judgment refers as the current capability of a pavement to serve for traffic to move. It is known as a ride quality measurement such as roughness and ranges from 5 (excellent) to 0 (very poor). Table 3-16 shows the PSR description based on FHWA interpretation as well as threshold from the Highway Performance Monitoring System (HPMS) Field Manual.

Table 3-16: PSR description based on the FHWA interpretation

PSR	Description	Rating (HPMS Field Manual)
5.0 – 4.0	Only new (or nearly new) superior pavements are likely to be smooth and distress free enough (sufficiently free of cracks and patches) to qualify for this category. Most pavements constructed or resurfaced during the data year would normally be rated in this category.	Good
4.0 – 3.0	Pavements in this category, although not quite as smooth as those described above, give a first-class ride and exhibit few, if any, visible signs of surface deterioration. Flexible pavements may be beginning to show evidence of rutting and fine random cracks. Rigid pavements may be beginning to show evidence of slight surface deterioration, such as minor cracks and spalling.	Fair
3.0 – 2.0	The riding qualities of pavements in this category are noticeably inferior to those of new pavements and may be barely tolerable for high-speed traffic. Surface defects of flexible pavements may include rutting, map cracking, and extensive patching. Rigid pavements in this group may have a few joint failures, faulting and/or cracking, and some pumping.	
2.0 – 1.0	Pavements in this category have deteriorated to such an extent that they affect the speed of free-flow traffic. Flexible pavement may have large potholes and deep cracks. Distress includes raveling, cracking, and rutting and occurs over 50 percent of the surface. Rigid pavement distress includes joint spalling, patching, cracking, and scaling and may include pumping and faulting.	Poor
1.0 – 0.0	Pavements in this category are in an extremely deteriorated condition. The facility is passable only at reduced speeds and with considerable ride discomfort. Large potholes and deep cracks exist. Distress occurs over 75 percent or more of the surface.	

All 95 road segments were used in the analysis while estimated PSR values alongside the respective IRI. The exponential function is the base relationship between PSR with IRI as shown in Equation 16.

$$\mathrm{PSR} = \alpha e^{-\beta * \mathrm{IRI}} \qquad (16)$$

Where α, β are the constant to be predicted and IRI in m/km

It was found that PSR has a strong relationship with IRI for the LVRR as shown in Figures 3-13. α = 5.952 and β = 0.15 are obtained as the representative parameters to the PSR vs IRI model for LVRR. Moreover, the statistical summary of the model is presented in Table 3-17.

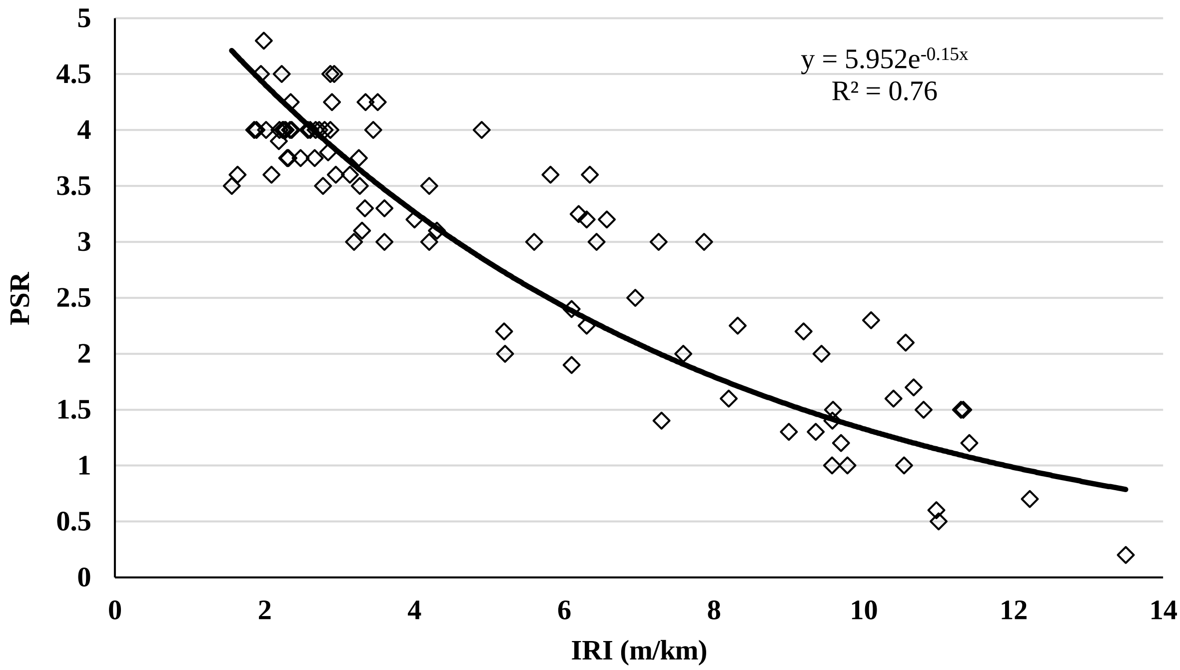

Figure 3-13: Relationship between PSR vs IRI

Table 3-17: Statistical Summary of the PSR vs IRI Model

Regression Statistics	
Multiple R	0.87
R-Squared	0.76
Standard Error	0.47
Observations	95

Parameter	***Df***	***SS***	***MS***	***F***	***Significance F***
Regression	1	102.036	102.037	468.571	3.17E-37
Residual	89	19.381	0.218		
Total	90	121.417			

3.7 Development of Major Distress Repair Cost Estimation Model based on IRI

Based on the developed multiple regression models three key distresses are identified as raveling, cracking and edge gap. The detailed distress densities of those distress are used to calculate the repair cost of major distress repair by using the regression analysis. The repair cost is calculated based on the Highway Schedule Rates-2019 [88] as presented in Table A-7 (Appendix A).

Non-linear model fitting was performed to obtain the best representation of the cost estimation model. The sigmoidal function which is shown in Equation 17 found to be the best-fitted cost estimation model concerning existing IRI as in Figure 3-14.

$$Distress\ Repair\ Cost = \frac{0.398}{0.00026 + e^{-IRI}} \tag{17}$$

Distress Repair Cost – Cost of repair for key distresses per square meter of the pavement (LKR), IRI – IRI in m/km

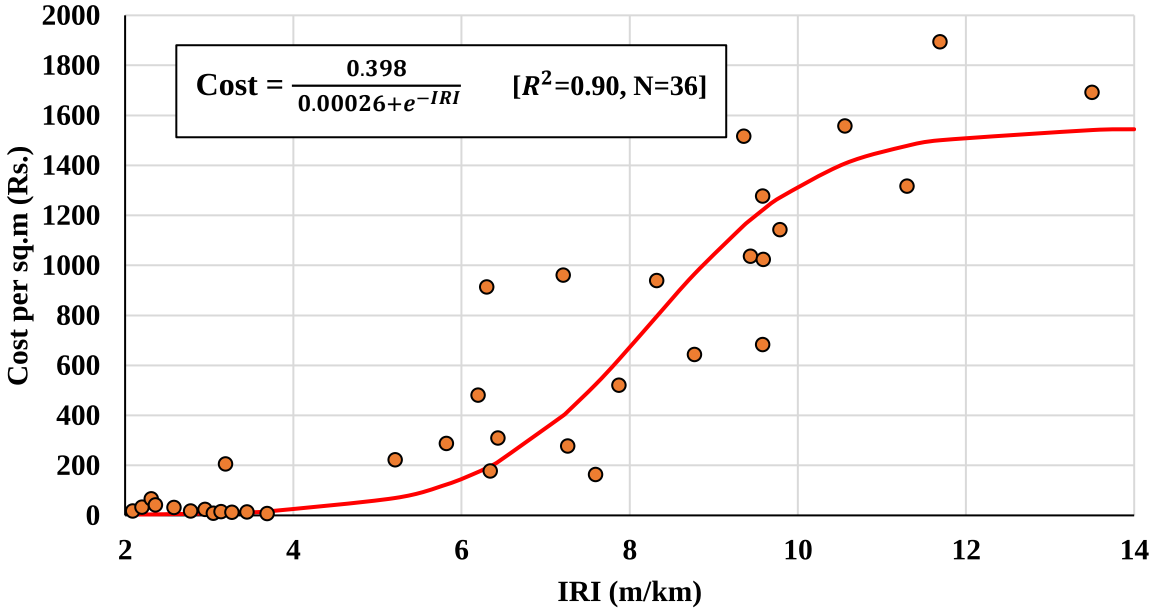

Figure 3-14: Cost Estimation Model for Major Distress Repair Concerning IRI

However, to calculate the distress repair cost, the cost values obtained from this model shall be added with the pothole patching cost. This would be implemented that IRI along with pothole counting is sufficient to calculate the key distress repair cost for LVRs network-level planning.

3.8 Identification of Maintenance and Rehabilitation Strategies for LVRRs

There are three types of work intervention criteria is adopted in Sri Lanka such as;

1. Routine Maintenance
2. Periodic Maintenance
3. Rehabilitation/ Improvement (Capacity Improvement and Structural Improvement)

Based on the identified maintenance types, repair strategies were established by reviewing works of literature and from the expert opinion as described below [26].

1. Flexible pavement
   - Routine maintenance – A combination of pothole patching, crack sealing, edge repair, patch raveling, drain repair, vegetation control
   - Periodic maintenance – Asphalt Concrete (AC) overlay using Hot Mix Asphalt (HMA)
   - Rehabilitation/ Improvement – Rehabilitation of existing pavement, Reconstruction, Road widening
2. Concrete pavement
   - Routine maintenance – A combination of joint sealing, diamond grinding, pothole patching, edge repair, vegetation control, drain repair
   - Periodic maintenance – Thin bonded overlay, Full-depth repair, diamond grinding
   - Rehabilitation/ Improvement – Slab replacement
3. Gravel roads
   - Routine maintenance – spot re-graveling, pothole repair, vegetation control, drain repair
   - Periodic maintenance – Gravel priming, Grading
   - Rehabilitation/ Improvement – Upgrade to single or double bituminous surface treatment pavement sections

(These M&R strategies selection is explained in section 2.7.1 and will be used in Chapters 4 & 5.)

3.9 Summary of the Chapter

This chapter describes the effective pavement condition evaluation criteria for LVRs. For that purpose, the study explored the applicability of smartphone-based roughness data as a novel pavement condition evaluating criteria by validating its accuracy with the Bump Integrator which is a Class III type roughness measurement equipment. The R-squared value between the two measurements was found as 0.78. Even though the relationship has shown that smartphone roughness slightly underestimates road roughness, still it can apply to LVRRs due to its cost-effectiveness, repeatability and easiness to use.

Next, it was assessed the ability of roughness results to represent pavement distress conditions. Regression models were developed to find the relationship between IRI and key distresses, found that Raveling, Edge Breaking, Pothole, Edge Gap, Pothole, Edge Breaking, Edge Gap has shown a good correlation with IRI as 0.61, 0.56, 0.55 & 0.52 respectively. However, cracking and patching was not provided a good correlation with the IRI progression.

Further, the combined effect of distress on IRI progression was evaluated by multiple-regression analysis for narrow roads and wider roads respectively and the models had an R-squared of 0.86 while pothole representing the dominant distress type. In wider roads the effect of the edge breaking and edge gap on IRI progression is negligible hence omitted by stratified sampling. Moreover, In wider road model, the existence of patching areas was reduced by the IRI.

Next, IRI progression was evaluated with the PCI and a non-linear relationship was found with an R-squared of 0.75 from the sigmoidal function. Further, the categorization was done between predefined IRI and PCI ranges, the results shown that the extreme conditions were similarly represented by the two indices. Furthermore, in the project prioritization, both indices were checked by Pearson rank correlation (r_s) and found a strong correlation of 0.72. That further concluded the capability of IRI to assess the overall pavement condition in network-level planning. In addition to the PCI index PSR is compared with the IRI by calculating the model parameters, and it was found that R-squared of 0.76 in the developed model.

Finally, it was identified the different strategies and maintenance operation types used in Sri Lanka as well as the IRI intervention levels. From the collected data, a cost estimation model for major distresses was developed. It was shown a strong predictive model with an R-squared of 0.9.

4 FRAMEWORK OF SINGLE-OBJECTIVE OPTIMIZATION APPROACH: MAXIMIZATION OF OVERALL NETWORK CONDITION

4.1 Introduction

In this chapter, it is proposed a framework for maximizing overall network condition in PMS for LVRRs. In decision-making criteria there are several components were linked together. The general analysis scheme/decision aid tool of the proposed PMS is presented in Figure 4-1.

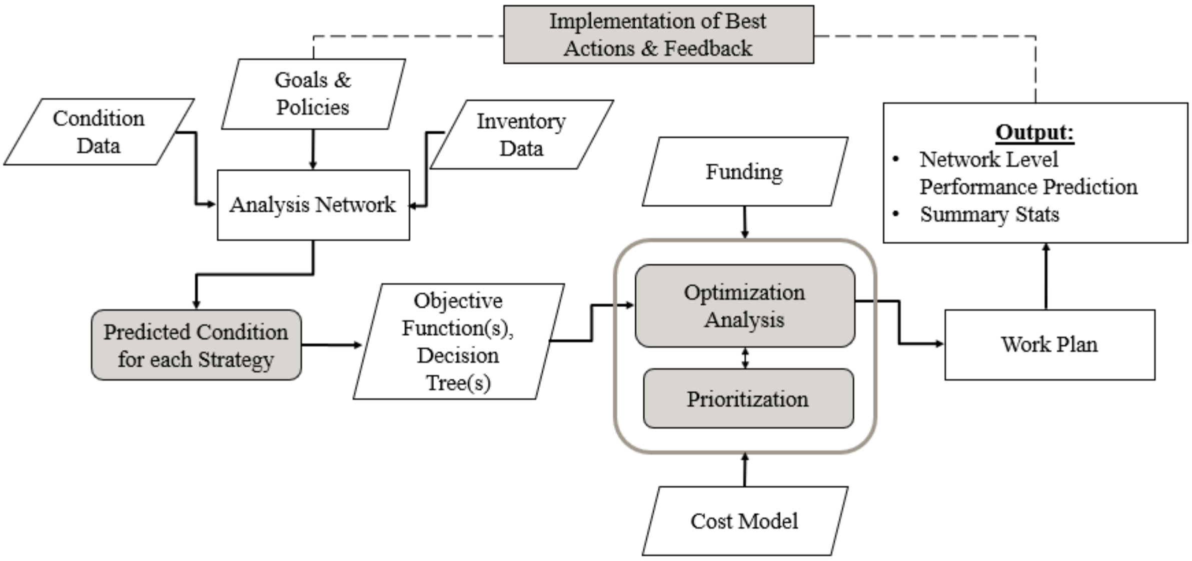

Figure 4-1: Analysis Scheme of the Proposed PMS for LVRRs

Moreover, the PMS has consisted of several components as shown in Figure 4-2: objectives of the analysis; data and the models about the road pavements; the constraints that the system must guarantee; and the outcomes. The primary objective in this analysis process was established as maximization of network condition while IRI was used as the pavement condition evaluation parameter. Since, low roughness pretends better pavement condition, to achieve the required objective; minimization of average network IRI was formulated as the objective function. Further, the results of the application are constituted by the M&R program, the cost report, and the functional quality report. The input data, the models about the road pavements, and the constraints that the system must guarantee are also presented in Figure 4-2.

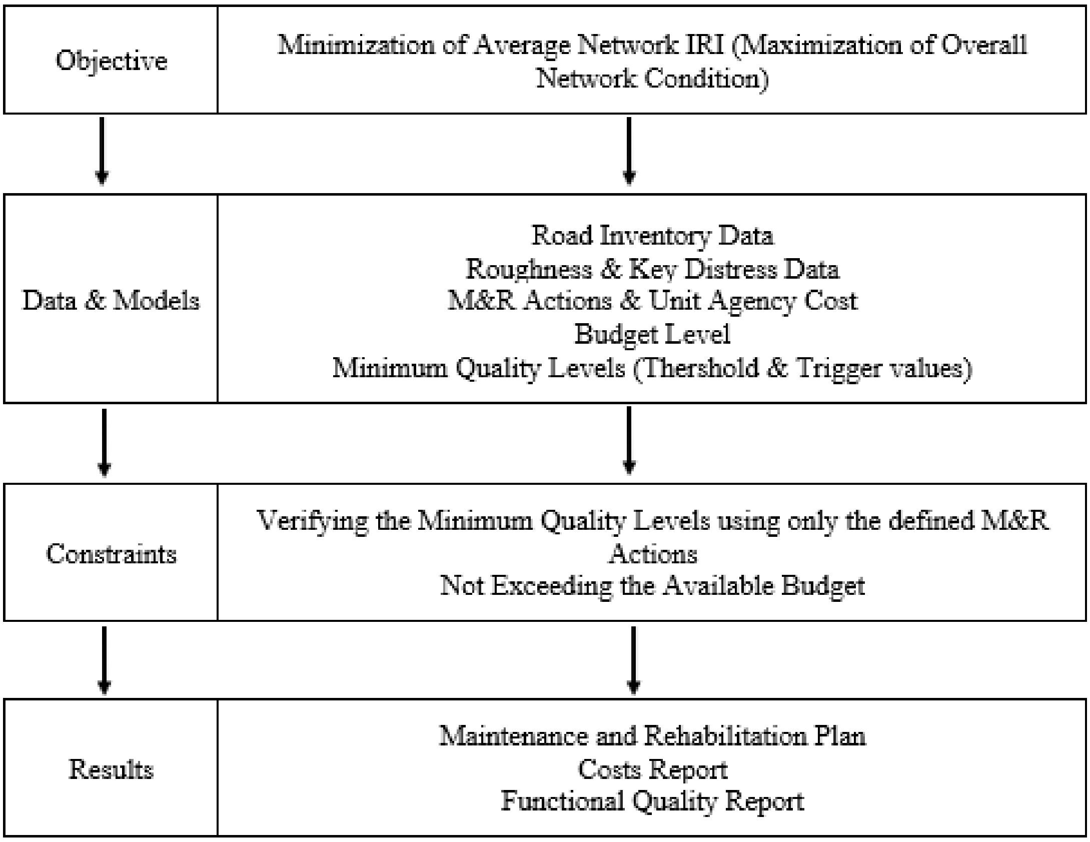

Figure 4-2: Pavement Management System Components

Two basic approaches have been followed; Integer Programming & the GA-based approach by reviewing the literature and previous studies. Both models have been used the same objective function, constraints, and decision tree while the definition of decision variables and solving methods was different in each other.

4.2 Approach-1: Minimization of Average Network IRI using Integer Programming

Formulation of the model was developed in a way that the performance level of the road network is maximized with a cost-effective maintenance strategy. Objective functions and constraints were defined as follows.

4.2.1 Definitions of the Parameters

The parameters which are used in the mathematical model are shown in Equation 18-21.

Three types of maintenance strategies have been defined as;

- r: The set of strategies (0 – Do Minimum, 1 – Periodic Maintenance, 2 – Routine Maintenance, 3 – Rehabilitation)

A strategy consists of a set of maintenance practices as defines in section 3.7.

Moreover, the road links are defining as follows.

- s: The set of road links (1, 2, 3……, n)

Q - Average network IRI value (in m/km)

Qrs - IRI of road section ‘s’ after applying the strategy ‘r’ (in m/km)

Ls - The length of road link ‘s’ (in km)

B - Total maintenance budget available for the financial year (in LKR)

Crs - The cost per kilometer for applying operation ‘r’ to road section ‘s’ (in LKR)

n - The number of road sections in the network

m - The number of operations used for road section ‘s’

4.2.1 Formulation of Objective Function(s)

- Minimize Average Network IRI:

$$\text{Minimize } \mathrm{Q} = \frac{\sum_{\mathrm{s}=0}^{\mathrm{n}} \sum_{\mathrm{r}=0}^{\mathrm{m}} \mathrm{Q}_{\mathrm{rs}} * \mathrm{L}_{\mathrm{s}} * \mathrm{X}_{\mathrm{rs}}}{\sum_{\mathrm{s}=1}^{\mathrm{n}} \mathrm{L}_{\mathrm{s}}} \tag{18}$$

4.2.2 Formulation of Constraint(s)

- Available Budget Level:

$$\text{Budget; } \mathrm{B} \geq \sum_{\mathrm{s}=1}^{\mathrm{n}} \sum_{\mathrm{r}=0}^{\mathrm{m}} \mathrm{C}_{\mathrm{rs}} * \mathrm{L}_{\mathrm{s}} * \mathrm{X}_{\mathrm{rs}} \tag{19}$$

- Annual Maintenance Operation:

$$\sum_{r=0}^{m} X_{rs} = 1 \tag{20}$$

Only one M&R strategy can be applied in a given analysis year.

Moreover, a decision tree that included generic constraints was used in the decision criteria. The constraints are described below and presented in Figure 4-3.

- If and only if $IRI_{ext,s} < 4$m/km, then $X_{1s}=X_{2s} = X_{3s} = 0$
- If and only if $IRI_{ext,s} > 7$m/km, then only $X_{3s} = 1$
- If and only if $IRI_{ext,s} > 4$m/km, then $X_{1s} =X_{2s} = 1$

Where $IRI_{ext,s}$ – Existing IRI value of the road link 's'

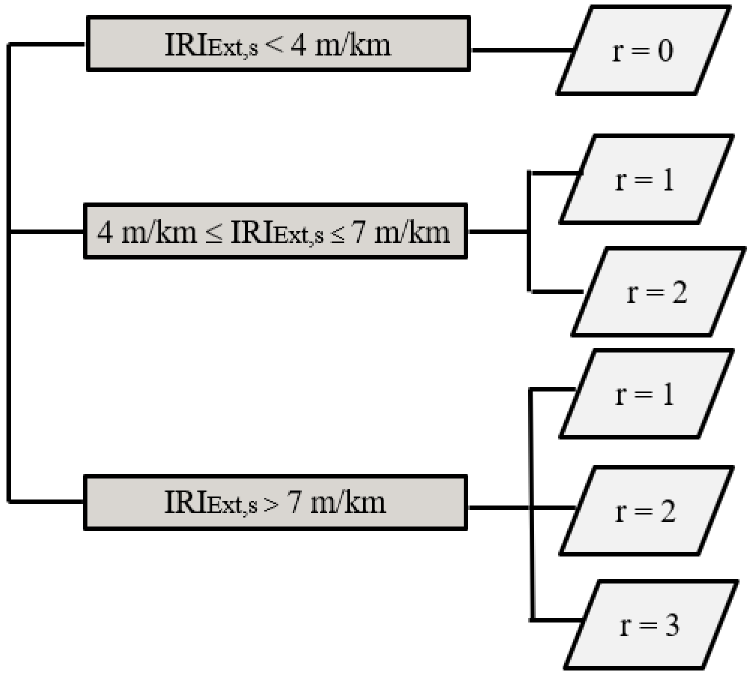

Figure 4-3: Decision-Tree Progression of Generic Constraints

4.2.3 Formulation of Decision Variable

$$X_{rs} \in \{0,1\} \tag{21}$$

Where Xrs is the binary decision variable with Xrs = 1; If strategy 'r' applied on-road link 's' & Xrs = 0; If strategy 'r' not applied on-road link 's'

After defining the objective functions, constraints, etc, the system was developed by using Java programming language and MySQL software. Java was used to create the front end which provides user interaction and MySQL was used to create a database of the system. The framework is consisting of three main stages of the decision-making process such as screening, prioritization for rehabilitation and network-level maintenance optimization process.

Prior to roads selected for the maintenance, roads that are in minimum acceptable condition (IRI < 4 m/km) filtered from the applying M&R actions. All of those roads are not considered in the maintenance program nonetheless do minimum strategy was assigned. After the screening, the remaining roads which have a condition poor than the defined rehabilitation threshold (IRI > 7 m/km) are selected for the rehabilitation work in the worst first ranking method until the allocated rehabilitation budget is fully utilized. The flow chart of screening and corrective maintenance selection is shown in Figure 4-4.

Then, remaining roads are continued to optimization approach using integer programming considering all possible combinations of maintenance strategies (in here routine maintenance (r=1) & periodic maintenance (r=2) were used).

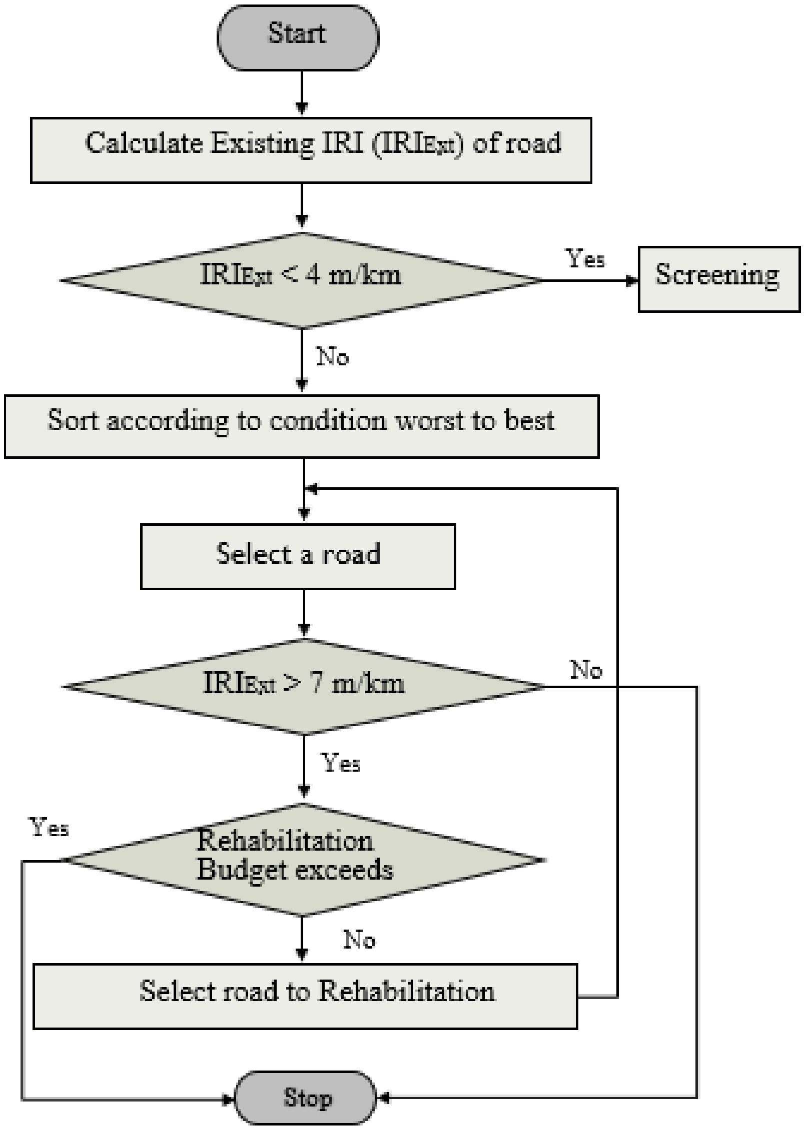

Figure 4-4: Flowchart of Screening and Rehabilitation Process

4.3 Case Study: Maintenance Program using Integer Programming

To illustrate the developed system, a sample of 27 road sections each having a length of 1 kilometer from Rathnapura PRDA were selected as presented in Table B-1. The existing average network IRI was 5.98 m/km. The total budget was set as Rs. 100 million and rehabilitation budget was allocated as a percentage of the total budget. The rehabilitation budget allocation percentage is varying from 5% to 95% with an increment of 5%. All budget allocation patterns were considered and the pattern which gives minimum average IRI was selected as the best solution.

In the present study, three different M&R strategies and do minimum strategy were considered as described, corresponding to seven M&R actions applied either individually or as a combination. The M&R actions types are presented in Tables 4–1. This M&R operations structure was defined for the PMS based on the practice of RDA, Sri Lanka. The M&R action costs considered in this study are presented in Table 4-1. The cost values are derived from National Road Master Plan 2018-2027, RDA [26] & Highway Schedule Rate, 2019 [88]. Furthermore, the strategies defined as in Table 4-2 as a combination of M&R actions.

Table 4-1: Types of M&R Actions

M&R Action	Description	Unit	Cost (LKR)
1	Vegetation Control	km	11,420
2	Drain Repair	km	16,990
3	Shoulder Repair	km	39,060
4	Pothole Patching (2m^2 standard size)	Nos	3,700
5	Major distress repair: Patch raveling + Crack sealing + Edge Break Repair	m^2	IRI based cost estimation model
6	AC overlay (50mm) HMA	m^2	1,320
7	Rehabilitation with 40mm HMA (Average width of 3.5 m section)	km	12,300,000

Table 4-2: Type of M&R Strategies

M&R Strategy (r)	Description	M&R Actions Involved
0	Do Minimum	1 + 2 + 3
1	Routine Maintenance	1 + 2 + 3 + 4 + 5
2	Periodic Maintenance	1 + 2 + 3 + 4 + 5 + 6
3	Rehabilitation	7

It was found that the 15% budget allocated for the rehabilitation pattern is the scenario that gives the minimum average IRI. In that, the total cost of Rs. 98.37 million and an average network IRI of 3.20 m/km achieved from the model as in Table B-2.

The following steps were followed in the process of finding the best M&R program for the selected road network.

- *Step 1: Screening* – 7 sections were screened from the maintenance process based on the value of IRI_{Ext}.
- *Step 2: Selection of roads for Rehabilitation* – Only one road section was identified for the rehabilitation under of 7m/km threshold value is the worst first prioritization method. The total cost of rehabilitation is Rs. 12.3 million and out of 7 only one section were selected due to budget constraints; Rs. 15 million. The selected sections for corrective maintenance are shown in Table B-2.
- *Step 3: Optimization Model for Maintenance Selection* – The remaining 19 road sections are selected for the maintenance process. The all remaining budget was used in this stage.

The analysis was further continued for different budget scenarios and evaluated the performance. It was found that the maximum condition of average IRI was 2.89 m/km in Rs. 134 million can be achieved when there is a sufficient budget available (no budgetary constraints scenario). By keeping that budget level as the base condition in the situations where 75%, 50% and 30% budget available for the road agency, network-level performance was evaluated as presented in Table 4-3.

Table 4-3: Network Level Performance for Different Budgetary Levels

Scenario Type	Budget Constraint (Rs. Million)	Average Network IRI (m/km)	Total Cost (Rs. Million)	Percentage Improvement	Budget Utilization Percentage
Scenario-1: No Budget Constraint	-	2.89	134.01	51.7%	-
Scenario-2: 75% of Required Budget Level (Case Study)	100	3.20	98.37	46.5%	98.4%
Scenario-3: 50% of Required Budget Level	67	3.68	66.69	38.5%	99.5%
Scenario-4: 30% of Required Budget Level	40	4.81	37.39	19.6%	93.5%

However, when the number of roads is increasing this approach seems to be difficult to solve the problem due to the large number of decision variables. Therefore, this approach is recommended to use when the number of pavement sections is lesser.

4.4 Approach-2: Minimization of Average Network IRI using Genetic Algorithm

A GA-based system to demonstrate the proposed framework of PMS was developed using Visual Basic Macro (VB) and Excel Analytic Solver platform. Visual Basic was used to create the front end to input data and Excel analytic solver platform was used to run the optimization model. Moreover, the analysis procedure was illustrated in Figure 4-5.

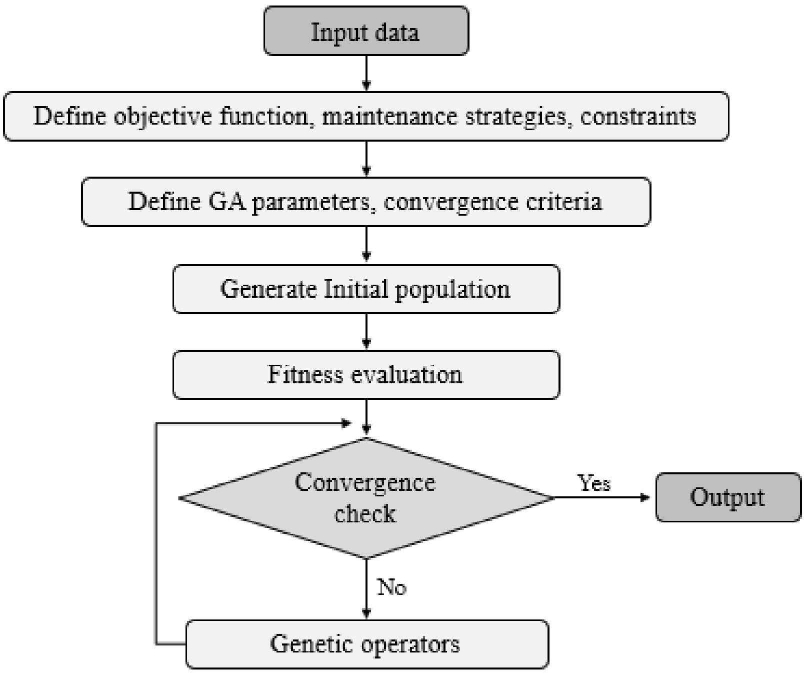

Figure 4-5: The Framework of the Developed PMS using Genetic Algorithm

The objective function, constraints and decision tree progression are the same as the previous approach as described in section 4.2. The formulation of decision variables in this approach was integer hence mathematical formulation is slightly different from the previous approach. The formulation is presented as in Equation 22-25:

Q – Average network IRI value (in m/km)

Qs (r) – IRI of road section ‘s’ after applying the strategy ‘r’ (in m/km)

Ls – The length of road link ‘s’ (in km)

B – Total maintenance budget available for the financial year (in LKR)

Cs (r) – The cost per kilometer for applying operation ‘r’ to road section ‘s’ (in LKR)

n – The number of road sections in the network

4.4.1 Formulation of Objective Function(s)

- Minimize Average Network IRI:

$$\text{Minimize } Q = \frac{\sum_{s=1}^{n} Q_s(r) * L_s}{\sum_{s=1}^{n} L_s} \tag{22}$$

4.4.2 Formulation of Constraint(s)

- Available Budget Level:

$$B \geq \sum_{s=1}^{n} C_s\,(r) * L_s \tag{23}$$

4.4.3 Formulation of Decision Variable

- Annual Maintenance Operation:

Where r = {Selected maintenance strategies for road link ‘s’}

$$r \in \{0,1,2,3\} \tag{24}$$

r: The set of strategies in integer decision variables (0 – Do Minimum, 1 – Periodic Maintenance, 2 – Routine Maintenance, 3 – Rehabilitation)

s: The set of road links (1, 2, 3……, n)

$$\forall s\ \exists r \text{ such that } n(r)=1 \tag{25}$$

The strategies are defined as in section 4.2.

Moreover, GA parameters were defined to get more accurate results in lesser time, from the iteration process. GA parameters such as population size, mutation rate, constraints convergence and random seed must be defined prior to run the optimization model.

4.5 Case Study: Maintenance Program using Genetic Algorithm

The same road network which was used in the case study in section 4.3 was analyzed with the system developed with GA. The main reason for use of this method is its capability of providing the optimum solution and suitability for a larger road network.

In the analysis process following GA parameters are assigned to run the optimization.

- Constraint convergence – 0.001

- Mutation rate – 0.8
- Population size – 100
- Random seed generation – 10
- Maximum iterations – 300

In this approach, the whole decision-making criteria are performed in one stage. In the Integer Programming technique, the decision-making criteria have consisted of three stages. The problem-solving method of GA is stochastic hence its capability the merge to the optimum solution would provide a better solution for the M&R decision-making in PMS.

From the optimization process, the average network IRI of 3.17 m/km was obtained under the total cost of Rs. 98.38 million. Moreover, Table B-3 presented the M&R strategies obtained from the optimum solution. This suggests that using GA as the solution algorithm can produce a better solution than the integer programming technique for the road network.

Moreover, the analysis is performed for different budgetary levels as in the previous case and the Table 4-4 shows the summary of network-level performance.

Table 4-4: Network Level Performance for Different Budgetary Levels

Scenario Type	**Budget Constraint (Rs. Million)**	**Average Network IRI (m/km)**	**Total Cost (Rs. Million)**	**Percentage Improvement**	**Budget Utilization Percentage**
Scenario-1: No Budget Constraint	-	2.89	134.01	51.7%	-
Scenario-2: 75% of Required Budget Level (Case Study)	100	3.17	98.38	47.0%	98.4%
Scenario-3: 50% of Required Budget Level	67	3.64	66.03	39.1%	99.6%
Scenario-4: 30% of Required Budget Level	40	4.63	37.39	22.6%	93.5%

Furthermore, a comparison between the two approaches has been made and network-level performance is shown in Figure 4-6. It is shown that GA based approach produced better condition improvement than the Integer programming approach.

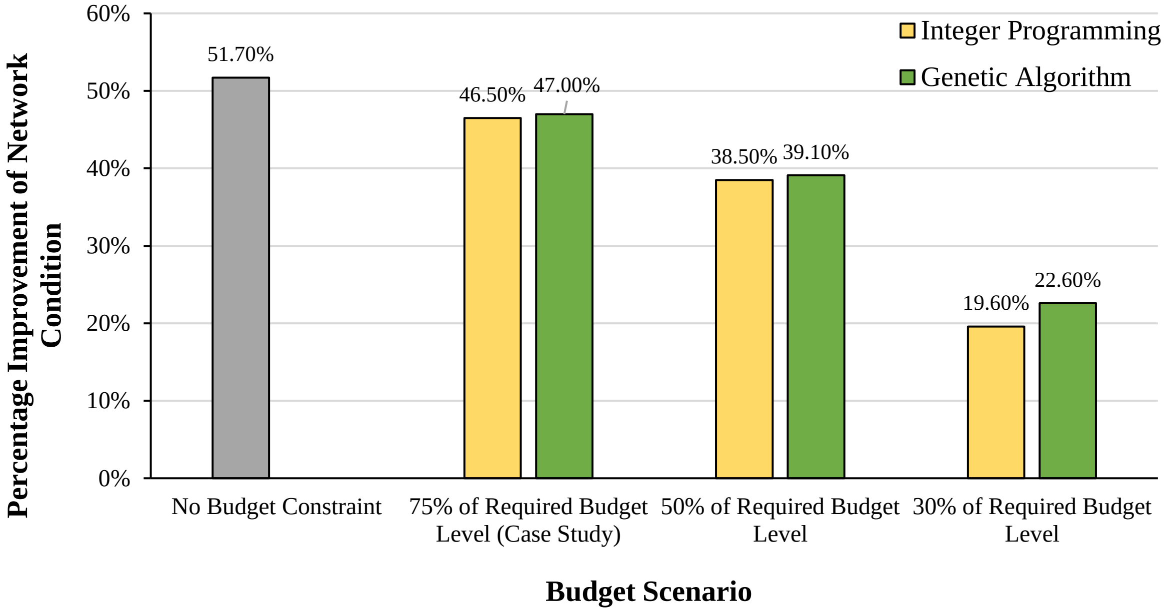

Figure 4-6: Comparison of Network Level Performance between Integer Programming vs Genetic Algorithm

4.6 Comparison of Engineering Judgement with Proposed Optimization Approaches in Maintenance Decision Making

Most of the local road agencies are taking the M&R decisions based on the subjective approach due to the non-existing of a proper system. Therefore, most of the time the decisions are ended up with a suboptimal solution. It is essential to evaluate the effectiveness of the two proposed approaches in maintenance decision-making. To illustrate that a case study was conducted by incoperating Engineering decision-making and compared their solutions with outcomes from Integer programming & GA-based approaches.

A hypothetical road network was developed with the following characteristics in the case study:

- Existing IRI - 6.79 m/km
- Three Types of Pavements –AC, Cement Concrete & Gravel
- Each with Length – 1 km

Moreover, the road inventories of the road network are presented in Table B-4. The Engineers were advised to take maintenance decisions by considering the IRI, ADT, Pothole density, etc. Moreover, they have notified the maintenance selection have three strategies (0 - Do Nothing, 1 - Routine Maintenance, 2 - Periodic Maintenance) and with the objective of minimization of average network IRI under three budget levels; Rs. 50, 75 & 100 million. 43 responses from highway engineers were collected and summarized as shown in Table B-5.

The same network was analyzed from the two proposed approaches and the best maintenance program was selected in each situation. There were 43 responses from Engineers hence normal distribution was plotted. Then, the best solution was found from the all feasible range of solutions which included the Engineers Judgements, Integer programming solution and GA solution as shown in Figure 4-7.

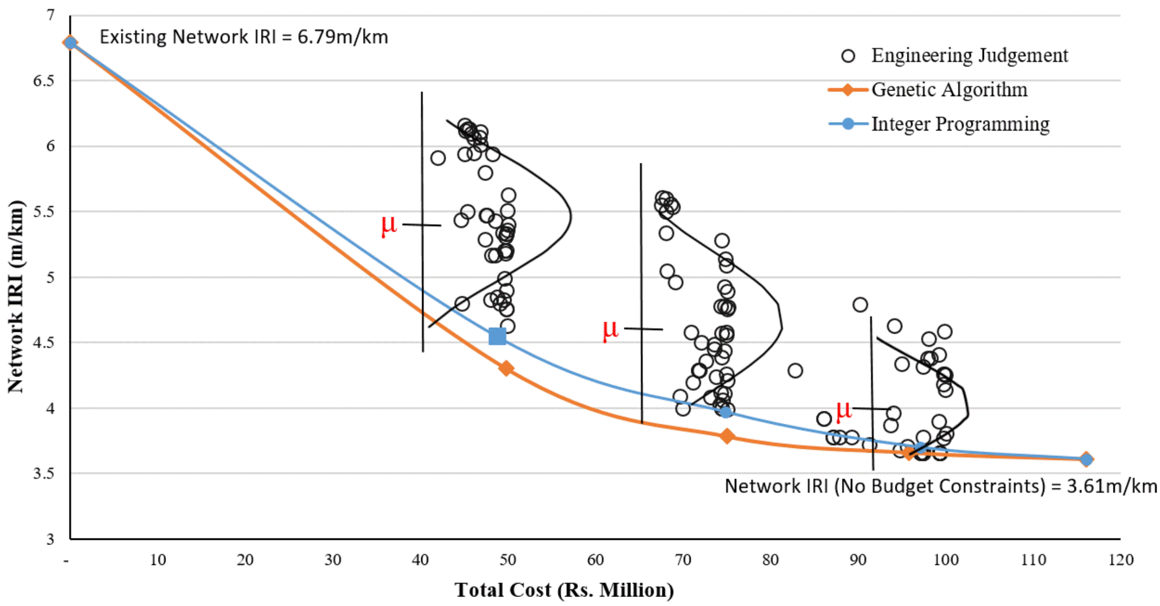

Figure 4-7: Set of Feasible Solutions for the Case Study

Table 4-5 shows that the comparison of the results concerning the three abovementioned methods.

Table 4-5: Comparison of Solutions from Engineering Judgement, Integer Programming and Genetic Algorithm for Different Budget Levels

Problem Solving Method		**Percentage Improvement**		
		50 Million Budget	**75 Million Budget**	**100 Million Budget**
Engineering Judgement	Range	9% - 32%	17% - 41%	29% - 46%
	Mean	20%	32%	41%
Integer Programming		33%	42%	46%
Genetic Algorithm (GA)		37%	44%	46%

From the results, it can be seen that Engineering judgment was varying in a broader range for three budgetary levels. Also, the solution obtained from the integer programming technique was close to the optimum solution but still, those are merged into a local optimal solution (sub-optimum solution). As per most of the previous studies in global, GA was provided the optimum solution/ the best maintenance program for this case study in all three budget levels.

However, when there is sufficient budget available in the M&R decision-making process most of the Engineer's decisions were close to the optimum solution/the best maintenance practice in-network level. In Rs. 50 Million budget level the mean of the Engineer Judgement is below par (17%) from the optimum condition. Even though, when there is sufficient budget available, most of the roads can be applied for periodic maintenance (r=2). Hence, Engineering Judgement and Integer programming are also close to the optimum solution. Table 4-5 is shown that in 75 Million and 100 Million budget levels, the difference between Engineering Judgement and optimum solution reduced to 10% and 5%. These results indicated that when there are budgetary constraints the optimization approach using GA was the most suitable method to find the best maintenance program in PMS. When there is a sufficient budget available, the significance of the optimization approach is low. However, most of the local road authorities in Sri Lanka are running with limited budget situations, therefore the developed systems, especially the GA-based optimization approach are useful in selecting the best maintenance program for LVRRs.

4.7 Summary of the Chapter

In this chapter, the focus is on developing the decision-making tools for the SOO approach. The objective function was defined in terms of IRI, to maximize the network condition. Therefore, the minimization of average network IRI was formulated as the objective function. The main outcome was the finding of the optimum work program for a given network. Two main approaches namely Integer Programming and GA-based approach were evaluated to find the optimal work program for a LVRR network. To support the decision making a decision tree was developed based on the intervention values identified from the literature review. Two approaches defined their decision variables differently; to optimize the same objective function. A case study was conducted by using both approaches and found that the GA-based system provided the optimal work program at all budgetary levels. Moreover, from the GA system, the network improvement was higher than approximately 4% compared with the

Integer Programming. The results have shown that the heuristic nature of the GA was helped to rendered near or optimal solutions while Integer Programming merged to a local optimum solution (sub-optimal level).

Next, another case study was conducted to compared Integer Programming, GA with the Engineer's objective judgment. The outcomes have shown that at the lower budget levels, Engineers' objective decision-making had significant variation in their decisions. In comparison to the objective decisions, both developed systems performed better and the GA-based system produced the optimum work program as the previous study. Interestingly, when there is a significant amount of budget available most of the Engineer's judgments were also close to the optimum solution. Also, very few Engineer's only ended up with the suboptimal level. That concluded when there are significant budget constraints a systematic approach is needed to find the optimum work program. Also, the GA-based system was selected for further system development when the road network is getting larger Integer programming no longer would produce the solutions accurately.

5 MULTI-OBJECTIVE OPTIMIZATION APPROACH BY INCOPERATING SOCIO-ECONOMIC IMPORTANCE IN NETWORK-LEVEL DECISION MAKING

In chapter 4, the single-objective optimization process has identified the optimum M&R program in terms of minimization of network IRI leaving to DMs in local road authorities in some situations the dilemma of either accepting or rejecting this single objective optimization solution. This is because when you only focused on the maximization of network conditions without knowing about the other aspects/objectives in the feasible solution space that solution may not reflect the best maintenance strategy. Especially, these LVRRs have more significance in a socio-economic sense, the importance of consideration of multiple objectives cannot be neglected. Therefore, in such situations, the Engineer should present a maintenance program that can optimize multiple objectives in addition to the maximization of network conditions. In this chapter, the study area was extended to solve a multi-objective problem incoperating socio-economic importance.

There are several additional steps needed to be added to the previous process to solve multiple objective problems. Moreover, the Pareto optimal set concept, and various solution selection techniques are used in the MOO approach. Based on the results get from the single-objective optimization approach in chapter 4, the GA-based approach was selected to model the MOO approach.

5.1 Incorporating of Socio-Economic Importance in the Decision-Making Criteria

5.1.1 Identification of Socio-Economic Priority Factors

Priority factors were identified through the literature survey from similar studies conducted in developing countries. Based on those, four main priority factors were selected namely Connectivity to the local road network, Importance to the community, Land use pattern and Traffic volume. To quantify the importance to the community, splitted into 4 sub-factors namely, the existence of civic centers, political interest, access to bus route, and availability of alternative routes during maintenance.

Moreover, Figure 5-1 is shown the distribution of priority indices in defining the socio-economic importance.

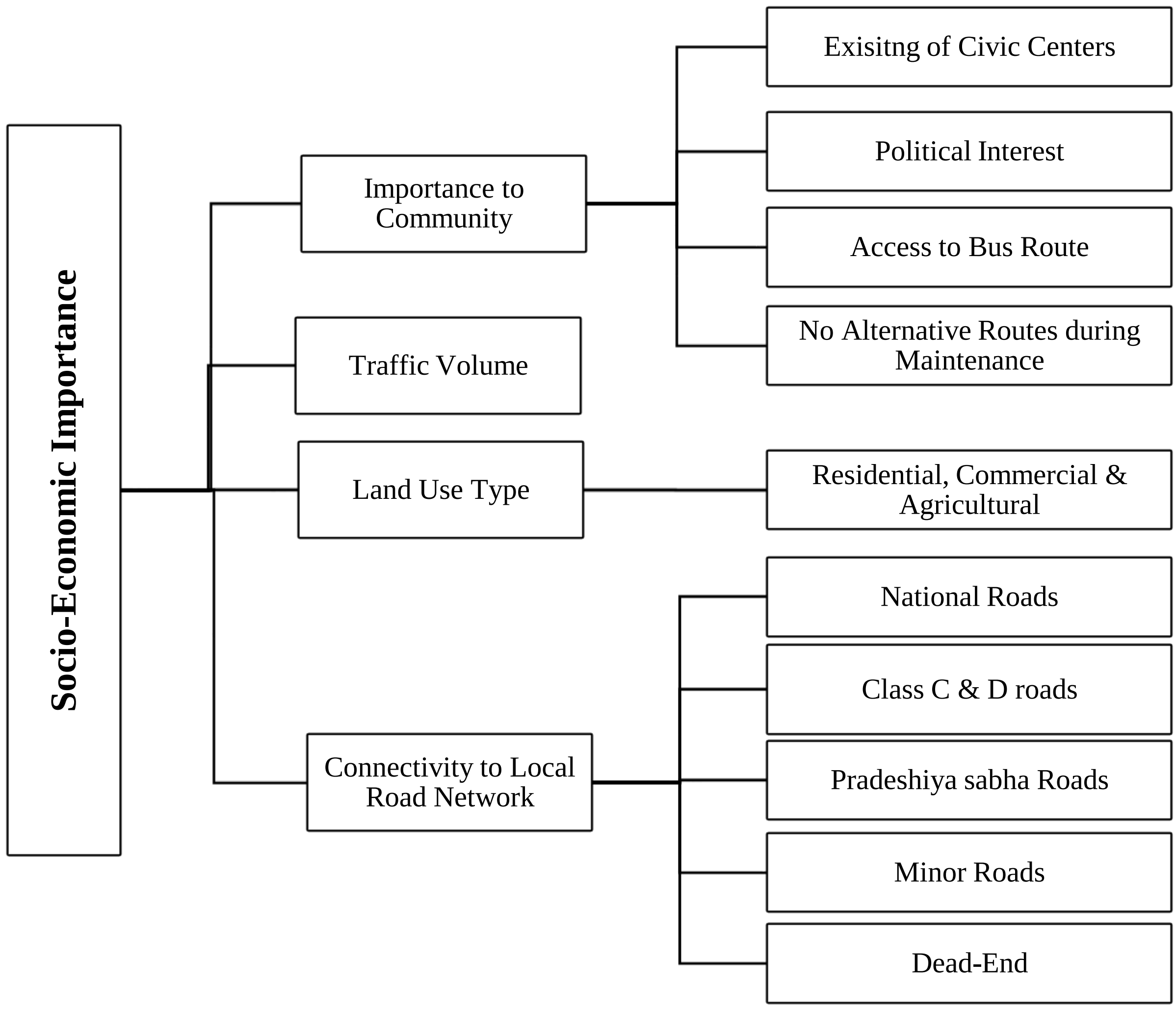

Figure 5-1: Priority Factors in Socio-Economic Importance

5.1.2 Formulation of Socio-Economic Importance Priority Index

The Priority Index (PI) was formulated as in Equation 26.

$$PI_s = \sum_{i=1}^{n} W_i * \frac{F_{i,s}}{F_{i,max}} \tag{26}$$

Where PI*s* – Socio-Economic Importance Priority Index of road segment ‘s’, W*i* – Weight of Priority factor ‘i’, F*i,s* – Value of priority factor ‘i’ for road section ‘s’, F*i, max* – Maximum value of the priority factor ‘i’ in the road network.

In the next step, scores were assigned for attributes based on the below criteria:

1. Traffic Volume – ADT was used and based on the value, relevant scores were defined.

2. Connectivity to Local Road Network – 10, 7, 5, 2 and 0 marks were assigned if the road section connects to national roads (class A & B), class C & D, Pradeshiya Sabha road, minor road and Dead-end respectively. Since both start node and end node are considered the maximum of 20 marks can be assigned to connectivity to local road network priority factor (in a situation when both nodes connect to national roads).

3. Land Use Pattern – Under residential, commercial and agricultural factors, scores for high, medium and low were assigned as 10, 5 and 2 respectively. These sub-categories were combined to represent one value in the land use pattern and maximum marks of 30 can be assigned (in a situation where there is a high extend of residential, commercial, and agricultural land uses were exist in a particular road segment). However, the definition of the extended level can be defined by the user or it can be present as an area percentage.

4. Importance to community – 10 marks was given for existing of civic centers such as Schools, Hospitals, Post office, Banks and Temples. Moreover, if a road link provides access to bus route, Political interest on the road and if there is no alternative roads during the maintenance going on 10 marks would be assigned to each.

Further, weightage for priority factors was defined based on the works of literature as presented in Table 5-1 [46]. However, defining scores and weightages can be rearranged based on the road agency's policies or decision-making criteria.

Table 5-1: Summary of Assignment of Scores for Attribute in Developing Priority Index [46]

Priority Factor	***Sub-Category***	***Score***	$F_{i,\,max}$	***The weightage (Wi)***
Connectivity to the local road network	A or B class road	10	20	35%
	C or D class road	7		
	Pradeshiya Sabha road	5		
	Minor road	2		
	Dead end	0		
Importance to Community	Existing of Civic Centers	10	40	20%
	Political Interest	10		

	Access to Bus Route		10		
	No Alternative Roads During Maintenance		10		
Land use pattern	Residential, Commercial, Agricultural	High	10	30	25%
		Medium	5		
		Low	2		
Traffic volume	- Based on the value -				20%

The maximum value attainable for the ratio of Fi,s to Fi, max is 1. Therefore, the maximum attainable value for Socio-Economic PI is limited to 100.

5.2 Formulation of Multi-Objective Optimization Approach

In this MOO approach, several tools were added to the previously developed GA-based SOO approach. In addition to the maximizing overall network condition, another objective function was formed as maximization of priority road condition. This was incorporated the socio-economic importance in the decision-making scheme and given the priority for the road segments which are significant in a socio-economic sense. Based on the PI, a set of priority road segments were identified. Then, the average IRI value of those roads was minimized by using the objective function; minimization of average IRI of priority roads. In this analysis procedure, a set of Pareto optimum solutions were generated concerning both objectives. Then the best solution selection procedure was proposed in two different ways based on the DM's choice.

The formulation of the analysis procedure of the MOO system is illustrated in Figure 5-2.

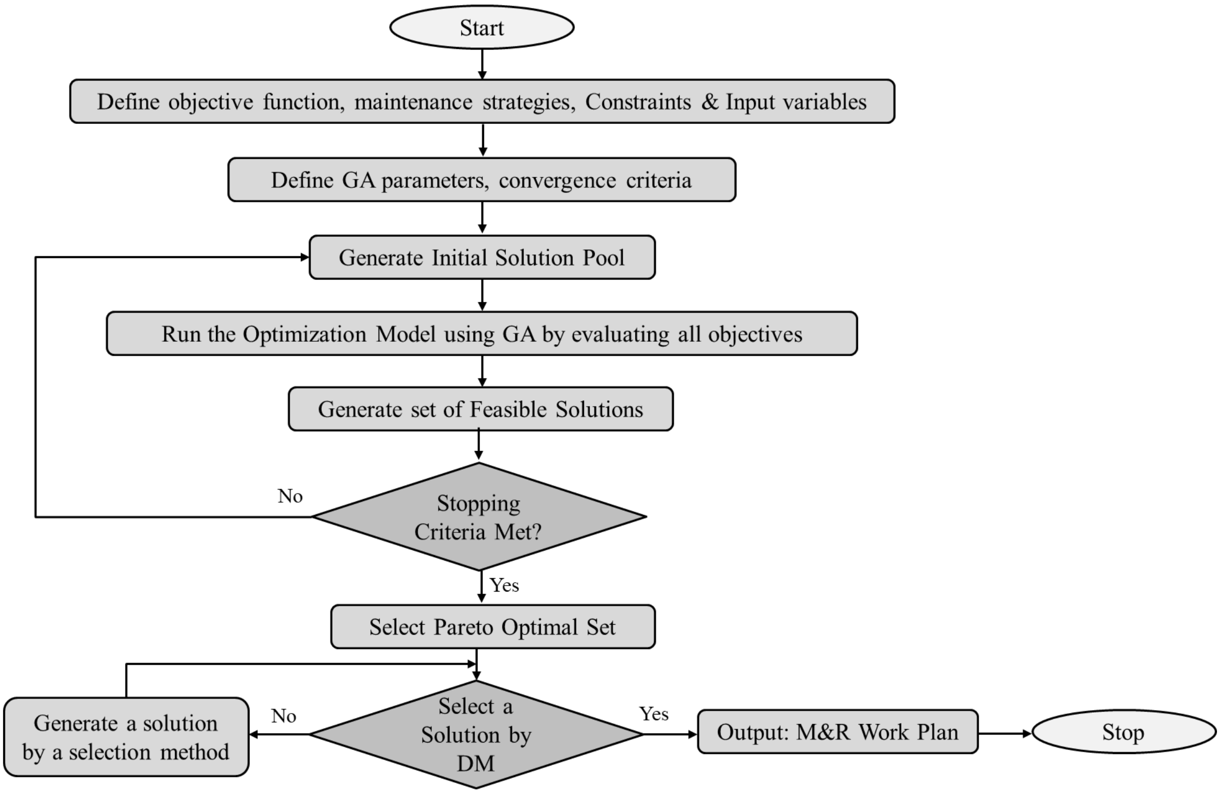

Figure 5-2: The Analysis Procedure of Multi-Objective Optimization Approach

The objective function, constraints, and decision variables are the same as the previous approach as described in section 4.4. In this MOO approach, a secondary objective was added as in Equation 27:

5.2.1 Formulation of Secondary Objective Function

- Minimize Priority Road Average Network IRI:

$$\text{Minimize } Q = \frac{\sum_{s=1}^{n} Q_{p,s}(r) * L_s}{\sum_{s=1}^{n} L_s} \tag{18}$$

Qp – Average IRI value of Priority roads (in m/km)

Qp,s (r) – IRI of road section ‘s’ after applying the strategy ‘r’ which is in priority road category ‘p’ (in m/km)

Ls – The length of road link ‘s’ (in km)

n – The number of road sections in the network

In addition to the previous approach, an extended decision tree is used as shown in Figure 5-3. In here, pavement type and traffic volume were added as parameters. Different threshold values were assigned for different pavement structures as per the literature and Sri Lankan practices. The analysis of literature and current practice in Sri Lanka is further illustrated in Table C-1 (Appendix C). However, the interventional level is customizable to the road agency decision making that input is no need to be constant in PMS. The intervention levels are changing based on the country/region, functional level, budgetary level in the road agency etc.

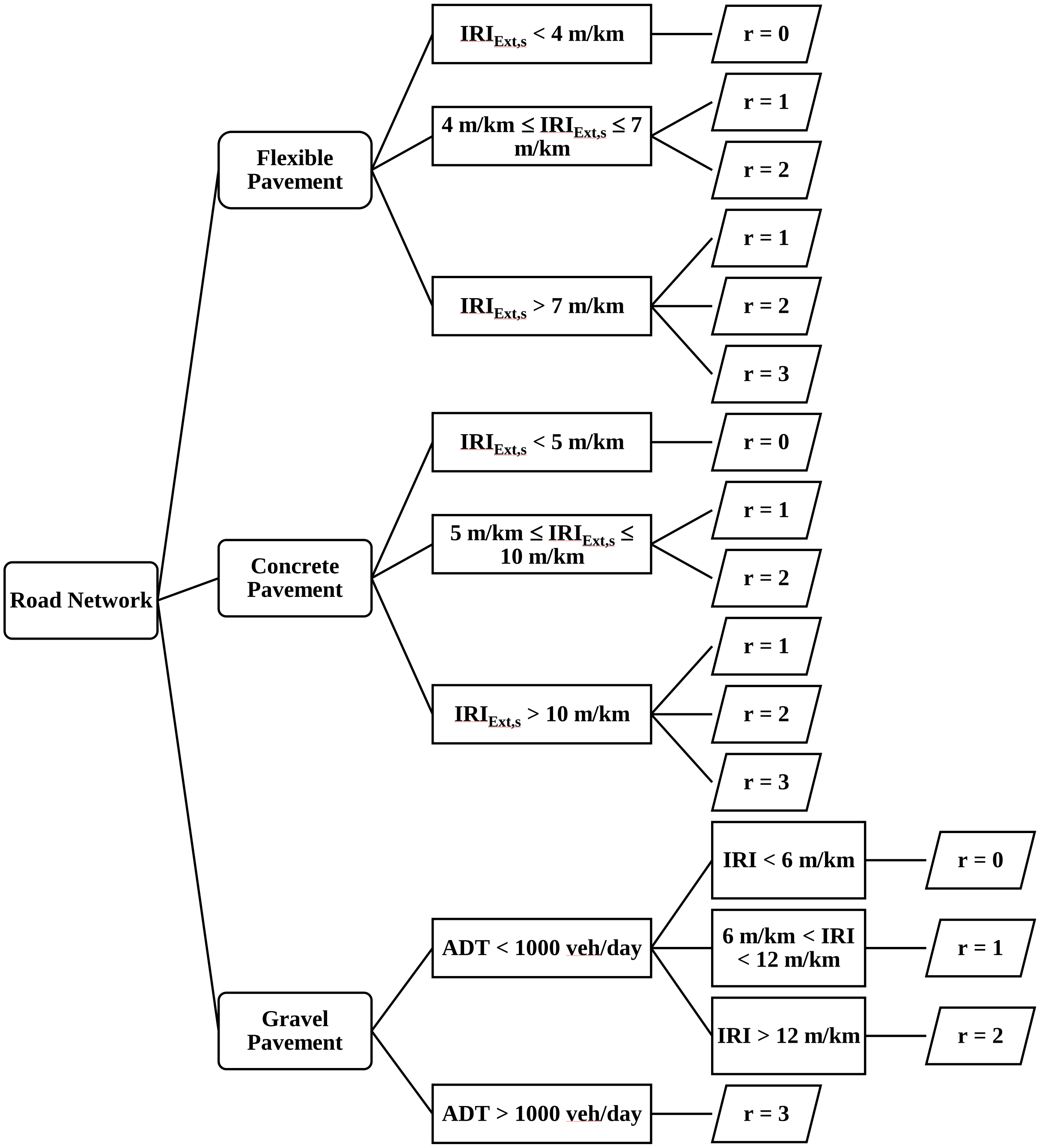

Figure 5-3: The Extended Decision Tree Progression for Different Pavement Type

The M&R operation cost values used in this approach are illustrated in Table 5-2. In addition to the previous operations, the maintenance practices which are applicable for rigid & gravel pavement sections were included. The cost values are derived from National Road Master Plan 2018-2027, RDA [26] & Highway Schedule Rate, 2019 [88]. Furthermore, the strategies are defined as presented in Table 5-3 as a combination of M&R actions.

Table 5-2: Types of M&R Actions used for Different Pavement Types

M&R Action	Description	Unit	Cost (LKR)
1	Vegetation Control	km	11,420
2	Drain Repair	km	16,990
3	Shoulder Repair	km	39,060
4	Pothole Patching (2m^2 standard size)	Nos	3,700
5	Major distress repair: Patch raveling + Crack sealing + Edge Break Repair	m^2	IRI based cost estimation model
6	AC overlay (50mm) HMA	m^2	1,320
7	Rehabilitation with 40mm HMA (Average width of 3.5 m section)	km	12,300,000
8	Retrofit Edge Drains	km	13,200
9	Shoulder Repair-Concrete	km	26,400
10	Thin Bonded Overlay	m^2	1,320
12	Full Depth Repair-Concrete	m^2	1,980
13	Re-graveling 100mm thick	m^2	134
14	Gravel grading	km	55,810
15	Gravel priming 100mm thick	m^2	471
16	Upgrade to SBST 15mm thickness	km	17.400,000

Table 5-3: Type of M&R Strategies in Different Pavement Types

M/R Strategy (r)	Description	M&R Actions Involved		
		Bituminous	Concrete	Gravel
0	Do Minimum	1 + 2 + 3	1 + 8 + 9	1 + 2
1	Routine Maintenance	1 + 2 + 3 + 4 + 5	1 + 4 + 5 + 8 + 9	1 + 2 +13
2	Periodic Maintenance	1 + 2 + 3 + 4 + 5 + 6	1 + 4 + 5 + 8 + 9 + 10	1 + 2 + 14 + 15
3	Rehabilitation	7	12	16

After formulation of the optimization model, the GA has generated the feasible solution set by satisfying all constraints including budgetary constraints and generic constraints in the decision tree (presented in Figure 5-3).

Given the mathematical formulation above, the next step is generating a Pareto optimal solution set. For this step, the approach based on GA was used and considering the objective of the objective functions (Both in minimization) relevant Pareto frontier was identified. A solution included in the Pareto front is defined as "a set of non-dominant solutions if there is no other solution that can improve at least one of the objectives without degradation of any other objective" [6]. In the case of minimizing two objectives in the study, optimal solutions can be found in the outer lower-left edge in the feasible region.

Since all Pareto optimal solutions can be considered as equally important with each other, many solutions exist. Therefore, the DM should identify the best solution on the Pareto front. Rather, the selection of a specific method depends on the users' preferences. However, in most situations, DM would not be able to select a better solution especially when there are multiple objective functions and a larger road network. Therefore, several methods have been proposed by researchers to select the best solution among the Pareto front as discussed in sections 5.2.2 & 5.2.3.

In this study, two methods were used; the Utopian Point method & Weighted Sum Method (WSM) by using a case study as presented in section 5.3.

5.2.2 Utopia Point Method

Generally, when solving the multi-objective optimization problem, it is difficult to select one solution to implement from the Pareto front. The Normal-Boundary Intersection method is used to identify the 'Anchor Points' of the Pareto frontier. The 'Anchor Points' are the farthest away Pareto point from the line in the direction of the normal vector. In this study, the Anchor Points were found by using the SOO approach. The optimum solutions found from the SOO approach were selected as the Anchor Points. Considering these multiple objectives, the point where normalized lines are intersecting is considered as 'Utopia Point' and this is the ideal solution for any multi-optimization problem. As the ideal solution may not be existing in most situations due to the conflicting objectives, the most preferable solution is considered in this method as the solution of the Pareto frontier that has the shortest normalized Euclidean distance concerning the ideal solution, computed using Equation 28. Moreover, Equation 28 presents the calculation of Euclidean distance for the bi-objective problem; minimize average network IRI (minimize Q) & minimize average IRI of priority roads (minimize Q_p).

$$D_i = \left[\left(\frac{Q_i - Q_{min}}{Q_{max} - Q_{min}} - Q^*\right)^2 + \left(\frac{Q_{p,i} - Q_{p,min}}{Q_{p,max} - Q_{p,min}} - Q_p{}^*\right)^2\right]^{\frac{1}{2}} \tag{28}$$

Where Di is the normalized distance between each Pareto solution point and the Utopia solution, Q^* and Qp^* are the normalized values for each objective of the Utopia solution; values of Q^* and Qp^* either 0 or 1 (when minimization objective equals to 0 & maximization objective equals to 1), Qmin and Qp, min is the minimum values obtained for each objective, Qmax and Qp, max is the maximum values obtained for each objective (maximum values are referred to existing IRI values)

5.2.3 Weighted Sum Method (WSM)

This is the simplest and most widely used approach globally [143]. As the name suggests, in this method, a set of multiple objectives combines into a single objective by using the user's predefined weightages for each objective. However, when setting the weights for an individual objective would depend on the magnitude of the objective function. Therefore, to cater to that, the proposed equation has suggested normalization of the objective functions to get the magnitude of each objective to the approximately same value. Equation 29 is shown the defined best solution selection criteria with the normalization of objective functions. As per that, in this approach both objectives should be minimized; hence Z which is the combined value should be minimized to achieve the best solution.

$$\text{Minimize } Z_i = W_Q * \left(\frac{Q_i - Q_{min}}{Q_{max} - Q_{min}}\right) + W_p * \left(\frac{Q_{p,i} - Q_{p,min}}{Q_{p,max} - Q_{p,min}}\right) \tag{29}$$

Where Z_i is the normalized value of each Pareto solution point and, W_Q and W_p are the weightages of average network IRI and average IRI of Priority roads respectively, Qmin and Qp, min is the minimum values obtained for each objective, Qmax and Qp, max is the maximum values obtained for each objective

The range of values for the various objective functions (Qmin, Qmax) and (Qp, min, Qp, max) was obtained by applying the optimization model considering only one objective at each time, i.e., varying the weight values vector (W_Q, Wp) among the extreme situations of (1,0) and (0,1), considering that initially all minimum values are 0 and all maximum values are 1.

5.3 A Case Study to Illustrate the Proposed Multi-Objective Optimization Approach

LVRR network in the Negombo area was selected with the following characteristics in the case study:

- Number of Road Segments – 94
- Existing IRI – 6.54 m/km
- Three Types of Pavements – Asphalt Concrete (AC), Cement Concrete (CC) & Gravel (GR)

The PI value was calculated based on the abovementioned criteria (section 5.1.2). The priority road segments were identified by using the calculated PI. The lower boundary is set as 50 for priority roads and it was found that 30 (32%) road segments have PI greater than or equal to 50. Hence, those were considered as the Priority roads in the selected road network. Since the lower boundary definition was an arbitrary value that can be changed based on the road agency's decision-making scheme. Apart from that, if any authority has identified the priority roads already, still this method is applicable. Moreover, the road inventories of the road network and the priority road segments are presented in Table C-2 (Appendix C).

However, several data types were missing in the calculation of PI such as Civic Centers and Access to cultural events. In this study, traffic volume was categorized into four levels and relevant scores were assigned as: 10-High Traffic, 7-Moderate Traffic, 5-Low Traffic, 3-Very Low Traffic.

As the first step, the total budget requirement was calculated based on the decision criteria. It was found that Rs. 933 million is required and a network IRI value of 3.60 m/km can be achieved with that (existing network IRI is 6.54 m/km). Moreover, to achieve the minimum acceptable level the budget of Rs. 239 million is required (25% of the total budget requirement) and the corresponding network IRI was 5.82 m/km. Then, three budget levels were evaluated using the single optimization model; 40%, 60% & 80% of the required budget level.

Before running the MOO model, the anchor points were established by applying the optimization model considering only one objective at a time. Table 5-4 illustrated the results obtained for all the above-mentioned scenarios from the optimization model; minimization of average network IRI.

Table 5-4: Summary of Results from Optimization Models for Different Scenarios

No	Scenario	Budget Level (Rs. Million)	Average network IRI (m/km)	Average Priority Road IRI (m/km)	Average Non-Priority Road IRI (m/km)
1	Existing Network Level	-	6.54	7.06	6.31
2	Minimum Acceptable Level	239	5.82	6.09	5.70
3	40% of the Total Budget Requirement	373	4.83	4.87	4.81
4	60% of the Total Budget Requirement	560	4.20	3.90	4.33
5	80% of the Total Budget Requirement	747	3.79	2.96	4.17
6	Total Required Budget level	933	3.60	2.74	6.31

Moreover, Figure 5-4 represents the improvement of network conditions with the different budgetary scenarios. Further, it has shown the percentage of the length of road segments in different IRI levels. Table 5-5 presents the percentage of road length in each IRI category.

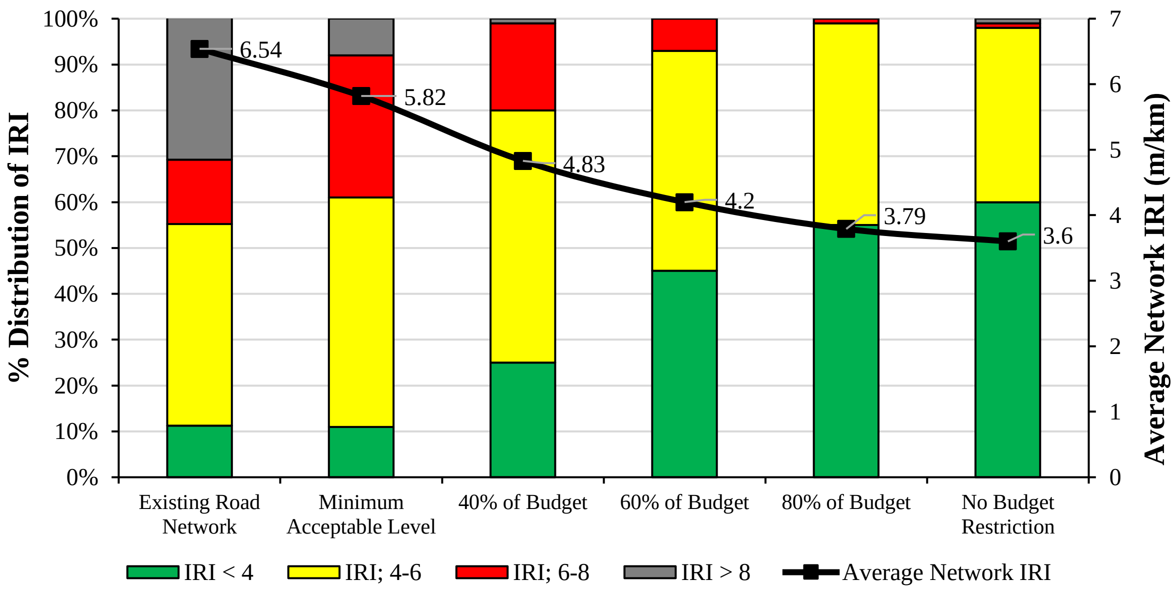

Figure 5-4: Improvement of the Network Condition for Different Budgetary Scenarios

Table 5-5: Percentage of Road Lengths in each IRI Ranges for Different Budget Scenarios

IRI Ranges	Existing Network Level	Minimum Acceptable Level	40% of Total Budget Requirement	60% of Total Budget Requirement	80% of Total Budget Requirement	Total Required Budget level
IRI < 4	11%	11%	25%	45%	55%	60%
IRI; 4-6	44%	50%	55%	48%	44%	38%
IRI; 6-8	14%	31%	19%	7%	1%	1%
IRI > 8	31%	8%	1%	1%	1%	1%

For the MOO approach, it needed to establish the anchor points. The average network IRI obtained from the model for 40%, 60% & 80% of the total budget requirement scenarios refer to the anchor points in respective scenarios. The three scenarios were repeated with the objective function; minimization of the average priority road IRI. The anchor points were found for both objectives by running the model separately as in Table 5-6.

Table 5-6: Anchor Points & Utopia Points for Different Budgetary Levels

No	Scenario	Anchor Points				Utopia Point (Ideal Solution)	
		Minimization of Average network IRI		Minimization Average Priority Road IRI			
		Average Network IRI (m/km)	Average Priority Road IRI (m/km)	Average Network IRI (m/km)	Average Priority Road IRI (m/km)	Average Network IRI (m/km)	Average Priority Road IRI (m/km)
1	40% of the Total Budget Requirement	4.83	4.87	5.14	4.25	4.83	4.25
2	60% of the Total Budget Requirement	4.20	3.90	4.64	2.77	4.20	2.77
3	80% of the Total Budget Requirement	3.79	2.96	3.83	2.74	3.79	2.74

Thereafter, the MOO model was performed for three different budgetary levels and a Pareto optimal set of solutions was generated. It has taken several iterations to produce the Pareto front.

The optimal solution searching for the multi-objective problem is conducted by using two approaches as described in sections 5.2.2 & 5.2.3. In the WSM, three criteria were analyzed by varying the weight values vector (W_Q, W_p) such as;

- (0.5,0.5) – Same weights assigned to both objectives
- (0.75,0.25) – Given the priority to minimize overall network IRI
- (0.25,0.75) – Given the priority to minimize priority road's IRI

The best value for each case was found from the multi-optimization model is illustrated in Table 5-7. Moreover, each obtained solution was compared with the ideal solution (utopia point) for the multi-objective problem. The ideal solution was non-existing due to the conflicts between objectives. The best solution can be recognized as the solution which is close to the ideal solution concerning both objectives.

Table 5-7: Results Obtained from Various Scenarios in Multi-Objective Optimization

Budget Level	Scenario	Average network IRI (m/km)	Average Priority Road IRI (m/km)
40% of the Total Budget Requirement (Rs. 373 million)	Ideal Solution for MOP	4.83	4.25
	Utopian Method	4.84	4.27
	WSM (W_Q=0.5,W_p=0.5)	4.92	4.39
	WSM (W_Q=0.75,W_p=0.25)	5.34	5.29
	WSM (W_Q=0.25,W_p=0.75)	5.05	4.91
60% of the Total Budget Requirement (Rs. 560 million)	Ideal Solution for MOP	4.20	2.77
	Utopian Method	4.23	2.95
	WSM (W_Q=0.5,W_p=0.5)	4.31	3.46
	WSM (W_Q=0.75,W_p=0.25)	4.26	3.30
	WSM (W_Q=0.25,W_p=0.75)	4.40	3.70
80% of the Total Budget Requirement (Rs. 747 million)	Ideal Solution for MOP	3.79	2.74
	Utopian Method	3.80	2.80
	WSM (W_Q=0.5,W_p=0.5)	3.89	3.14
	WSM (W_Q=0.75,W_p=0.25)	3.82	2.92
	WSM (W_Q=0.25,W_p=0.75)	3.81	2.86

Most importantly, it can be seen that the Utopian method was solved the multi-objective problem with the nearest to the ideal solution in all three budgetary levels. In the WSM, due to its subjectiveness, the solutions were merged into a suboptimal level. However, when both objectives were considered as the similar importance (W_Q=0.5, W_p=0.5), the output was better than biased situations.

Further, the Figure 5-5 & 5-6 represents the variation in each objective function for the different scenarios and analysis methods. In addition to the MOO methods, the results from the SOO are included here.

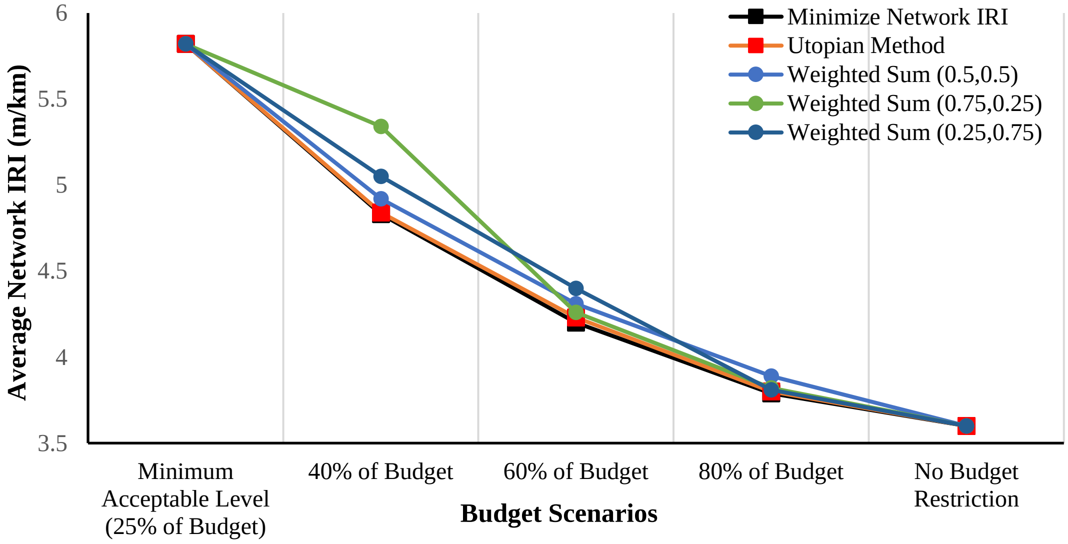

Figure 5-5: Comparison of Average Network IRI from Different Multi-Objective Optimization Methods

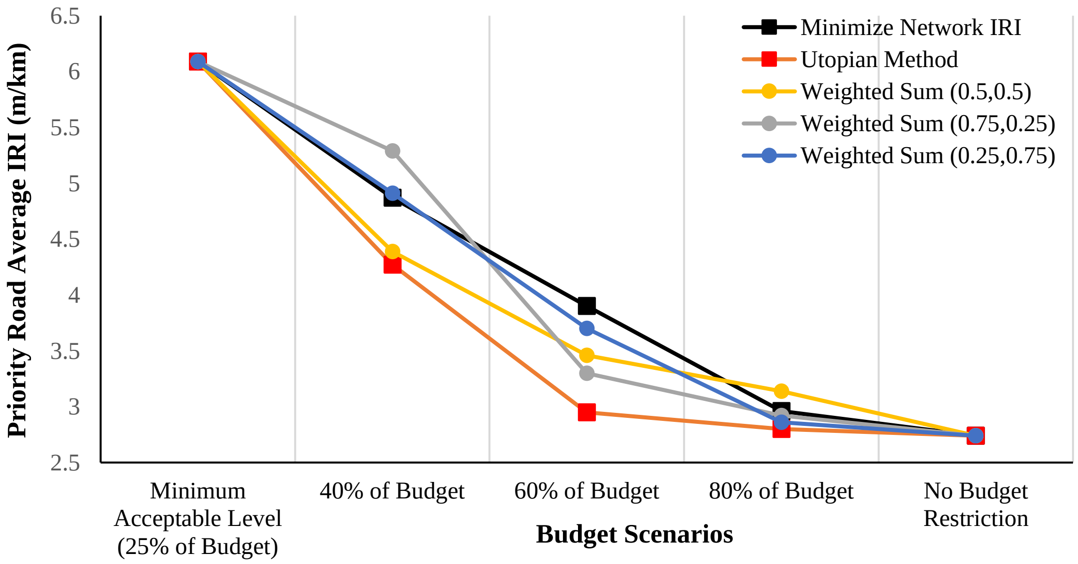

Figure 5-6: Comparison of Average Priority Road IRI from Different Multi-Objective Optimization Methods

From that it can be seen clearly, average network condition remained as it is in the single optimization approach when compared with the utopian method. However, the results obtained from the WSM slightly reduced the overall network condition. Interestingly, the utopian method was given the best condition for priority roads in the multi-objective problem. Table C-3 (Appendix C) is illustrated the selected maintenance strategies for each road segment in three budgetary levels. It provides sufficient evidence that rather than using the single optimization approach (minimization of average network IRI) with the use of minimizing average priority road IRI as the second objective was produced better conditions for the priority roads. Therefore, the utopian method gives priority to the roads which are significant in the socio-economic sense. WSM also provides a better condition for the priority roads when compared with the single optimization solution.

So, from the results from the case study, it was concluded that the multi-objective optimization approach provides better road conditions for the priority roads and the utopian method of selecting optimum solution would give the best solution for the multi-objective problem.

However, in the 80% budget level, there was no significant difference among the solutions and those were closer to the optimum condition (Figure 5-6). That is because, when there is sufficient budget available for the maintenance, no real impact of the optimization method (either single or multi-objective) or solution selection method. The case study has confirmed that aspect clearly from the outcomes.

5.4 A Case Study to Illustrate the Proposed Multi-Objective Optimization Approach by Incoperating Safety Performance

5.4.1 Formulation of Safety Performance as the Secondary Objective Function

A safety performance evaluation criterion which was proposed by Cafiso et al. (2007) was adopted in this case study [154]. It proposed the Cumulative Safety Index (CSI) to measure safety performance. In a situation where the CSI is higher that refers to the road have a higher amount of safety issues which determined from pre cash factors and vice-versa.

The objective function was proposed in terms of Cumulative Safety Index (CSI) as shown in Equation 32 and the decision variables are defined as in Equation 33.

- Minimize Average Network CSI (S):

$$\text{Minimize } S = \frac{\sum_{s=1}^{n} \mathrm{CSI_s(k)} * \mathrm{L_s}}{\sum_{s=1}^{n} \mathrm{L_s}} \tag{32}$$

S – Average Network CSI value

CSI_s (k) – CSI value of road section ‘s’ after applying the safety improvement strategy ‘k’

Ls – The length of road link ‘s’ (in km)

n – The number of road sections in the network

Where k_S = {Safety Improvement strategies for road link ‘s’}

$$\mathrm{k_s} \in \{0,1,2,3\} \tag{33}$$

$k_s = 0$: Do nothing, $k_s = 1$: Refers to the clearing of roadside obstructions, lane marking, installing warning signs, and marking pedestrian crossings, $k_s = 2$: Refers to super elevation adjustments, curve geometry arrangements, constructing pedestrian walkways, installing guardrails, covering open drains, and edge corrections, $k_s = 3$: Refers to the combination of strategy 1 and strategy 2 where all defined safety improvement strategies were included.

Moreover, a simple generic constraint was added to the decision tree as in Equation 34.

- Safety performance;

$$\text{If } (\mathrm{CSI})_s < 200, \text{ then } k_s = 0 \tag{34}$$

This is only for illustration and based on the preference of the DM the generic constraint can be changed or added.

5.5 A Case Study by Incoperating Safety Performance

To demonstrate the applicability of the proposed MOO approach incorporating safety performance, a sample of 25 roads from the rural road network in Sri Lanka was selected. The road network consists of a total length of 48.4 km. The initial average network IRI, and initial average network CSI were obtained as 5.56 m/km and 489 respectively with ADT less than 3,000 veh/day. Three major types of pavement structures were considered for the study: flexible, rigid, and gravel. The input data includes dimensions of each road, post pavement condition, and safety condition predictions in terms of IRI and CSI, respectively. Cost estimation for improving pavement condition and safety condition was adopted as per the results based on (Pasindu *et al*. 2020) [155]. Table C-4 (Appendix C) is illustrated the road inventories collected for the road network.

As the first step, the total budget requirement was calculated based on the decision criteria. It was found that Rs. 163 million is required and a network IRI value of 3.60 m/km can be achieved with that. Moreover, to achieve the minimum acceptable level the budget of Rs. 33 million is required (20% of the total budget requirement) and the corresponding network IRI was 5.04 m/km. Then, three budget levels were evaluated using the single optimization model; 40%, 60% & 80% of the required budget level. The respective values were determined for the safety performance for the three budgetary levels. After a series of trial calculations, suitable GA parameters are acquired as follows: population size = 150, chromosome length = 25, mutation probability = 0.01, maximum generation = 100, crossover probability = 0.5. The Anchor points and ideal solution for each budgetary level including total budgetary requirement condition are illustrated in Table 5-8.

Table 5-8: Anchor Points & Utopia Points for Different Budgetary Levels

No	Scenario	Anchor Points				Utopia Point (Ideal Solution)	
		Minimization of Average Network IRI		Minimization Average CSI			
		Average Network IRI (m/km)	Average CSI	Average Network IRI (m/km)	Average CSI	Average Network IRI (m/km)	Average CSI
1	40% of the Total Budget Requirement	4.17	489	5.56	252	4.17	252
2	60% of the Total Budget Requirement	3.83	489	5.56	220	3.83	220
3	80% of the Total Budget Requirement	3.60	489	5.56	201	3.60	201
4	Total Required Budget	3.54	489	5.56	161	3.54	161

Thereafter, the MOO model was performed for four different budgetary levels and a Pareto optimal set of solutions was generated. It has taken several iterations to produce the Pareto front.

The optimal solution searching for the multi-objective problem is conducted by using two approaches as described in sections 5.2.2 & 5.2.3. In the WSM three criteria were analyzed by varying the weight values vector (W_Q, W_S) such as;

- (0.5,0.5) – Same weights assigned to both objectives
- (0.75,0.25) – Given the priority to minimize overall network IRI
- (0.25,0.75) – Given the priority to minimization of average CSI value

Where Ws is the weightage assign for the safety performance.

The best value for each case was found from the multi-optimization model is illustrated in Table 5-9. Moreover, each obtained solution is compared with the ideal solution (utopia point) for the multi-objective problem. The ideal solution is non-existing due to the conflicts between objectives. The best solution can be recognized as the solution which is the nearest to the ideal solution concerning both objectives. In the WSM, the best solution was selected from among the different combinations used.

Table 5-9: Selected Pareto Optimal Solutions from Various Scenarios in Multi-Objective Optimization

Budget Level	Scenario	Average network IRI (m/km)	Average CSI value
40% of the Total Budget Requirement (Rs. 65 million)	Ideal Solution for MOP	4.17	252
	Utopian Method	4.41	277
	WSM (W_Q=0.5,W_S=0.5)	4.37	281
60% of the Total Budget Requirement (Rs. 98 million)	Ideal Solution for MOP	3.83	220
	Utopian Method	3.99	273
	WSM (W_Q=0.75,W_S=0.25)	3.98	278
80% of the Total Budget Requirement (Rs. 131 million)	Ideal Solution for MOP	3.60	201
	Utopian Method	3.89	260
	WSM (W_Q=0.5,W_S=0.5)	3.89	253
Total Budget Level (Rs. 163 million)	Ideal Solution for MOP	3.54	161
	Utopian Method	3.70	236
	WSM (W_Q=0.5,W_S=0.5)	3.60	266

Further, Figures 5-7 & 5-8 are shown the percentage improvement of each objective in different budgetary scenarios.

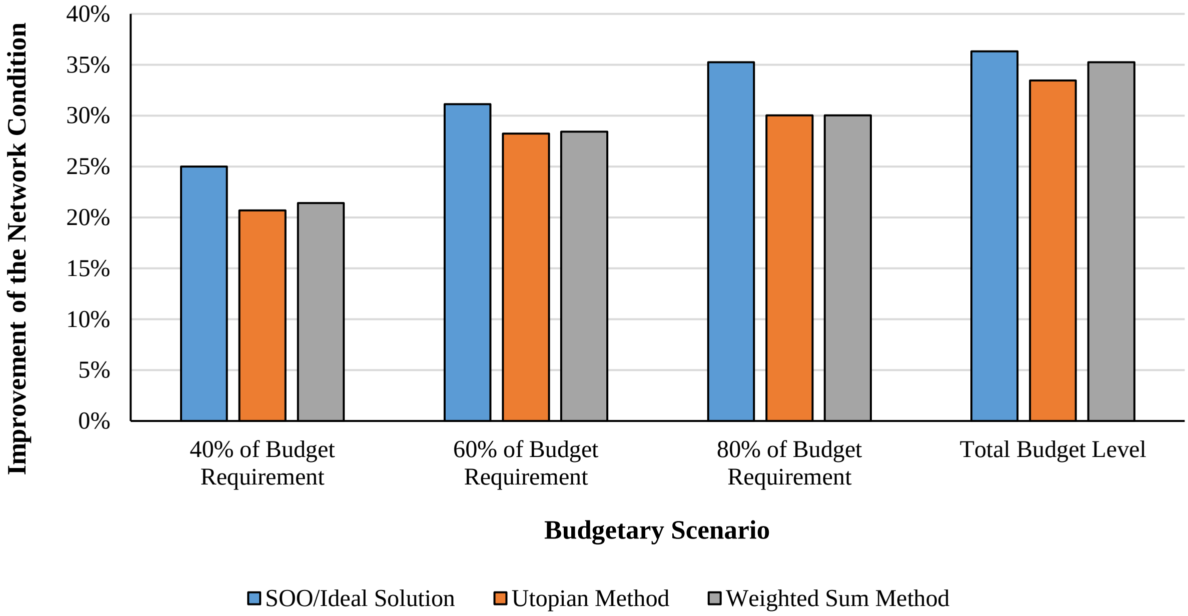

Figure 5-7: Percentage Improvement of Pavement Condition in Various Budgetary Scenarios

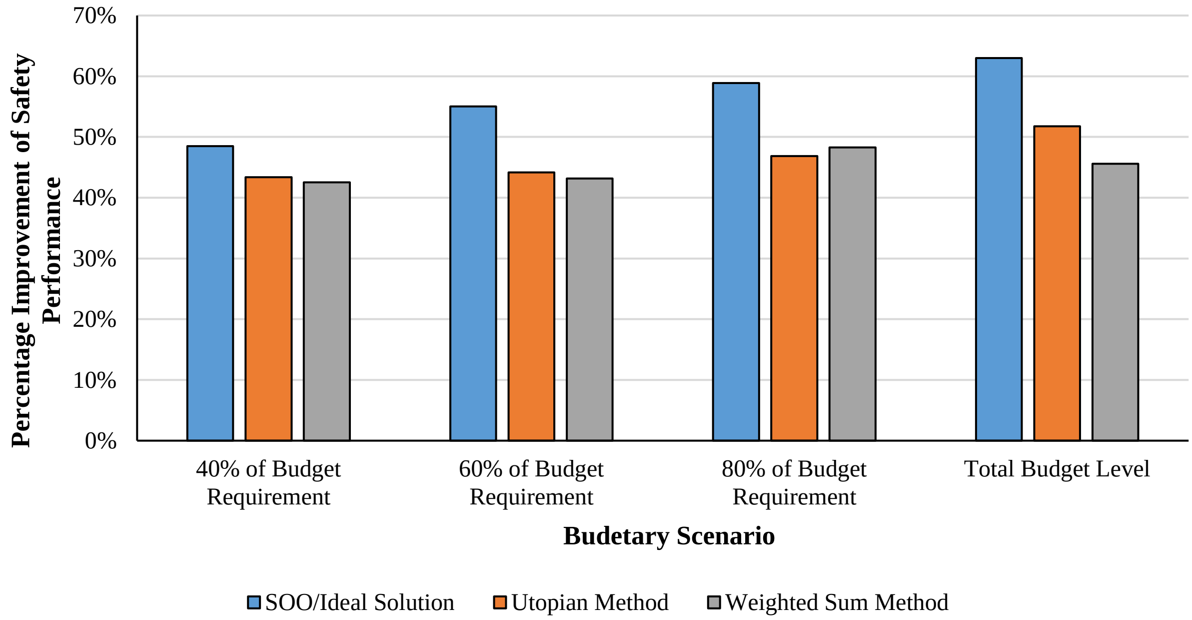

Figure 5-8: Percentage Improvement of Safety Performance for Various Budgetary Scenarios

Furthermore, Figure 5-9 is shown the Pareto front and the set of the best solution (including optimal solutions) in graphical view. That gives a clear indication of the results obtained from each method.

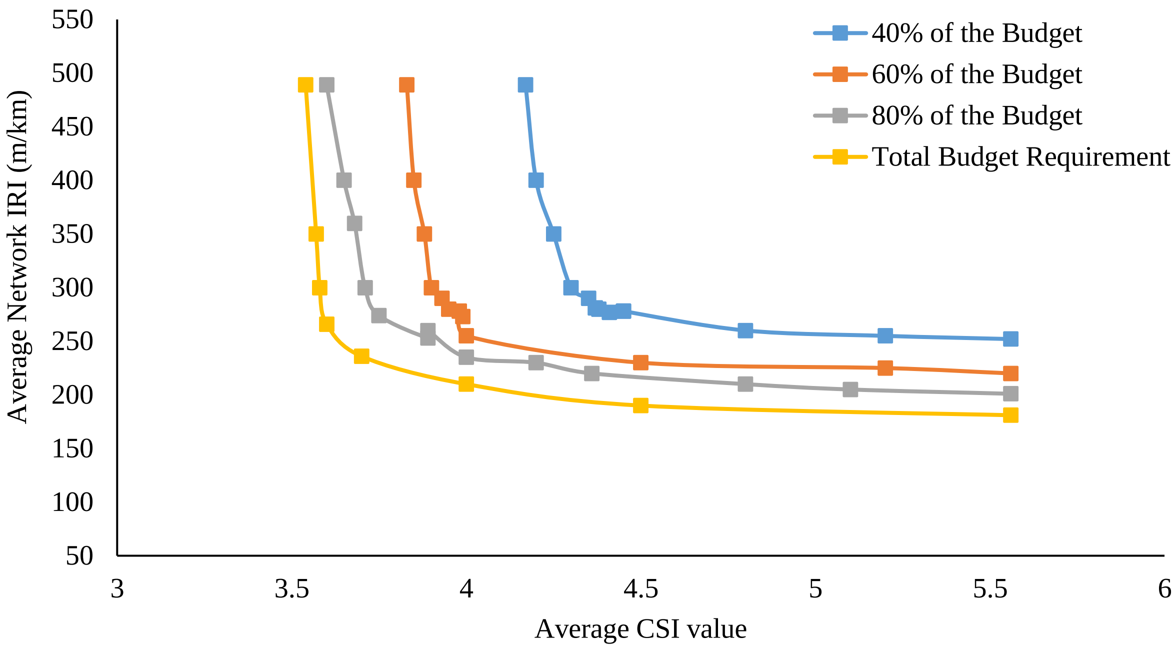

Figure 5-9: Pareto Fronts for Different Budgetary Scenarios

The plot of Clustered Stacked Columns in Figures 5-10 represents the optimal solutions obtained in the SOO approach and MOO approach. In each budget scenario three solutions were compared; SOO, MOO-Utopian & MOO-WSM. From the results, It can be seen that rather than spend allocated funds to optimize one objective, the use of the MOO criterion provided more beneficial to the road agencies and users. When the same budget level spends on MOO the improvement was nearly 2.5 times from the SOO approach. Moreover, in the percentage improvement of objectives, the Utopian method has been provided the most effective solution among the Pareto front in most of the situations. However, the WSM also provided a better solution for the multi-objective problem, especially in the scenario when both objectives were considered equally important.

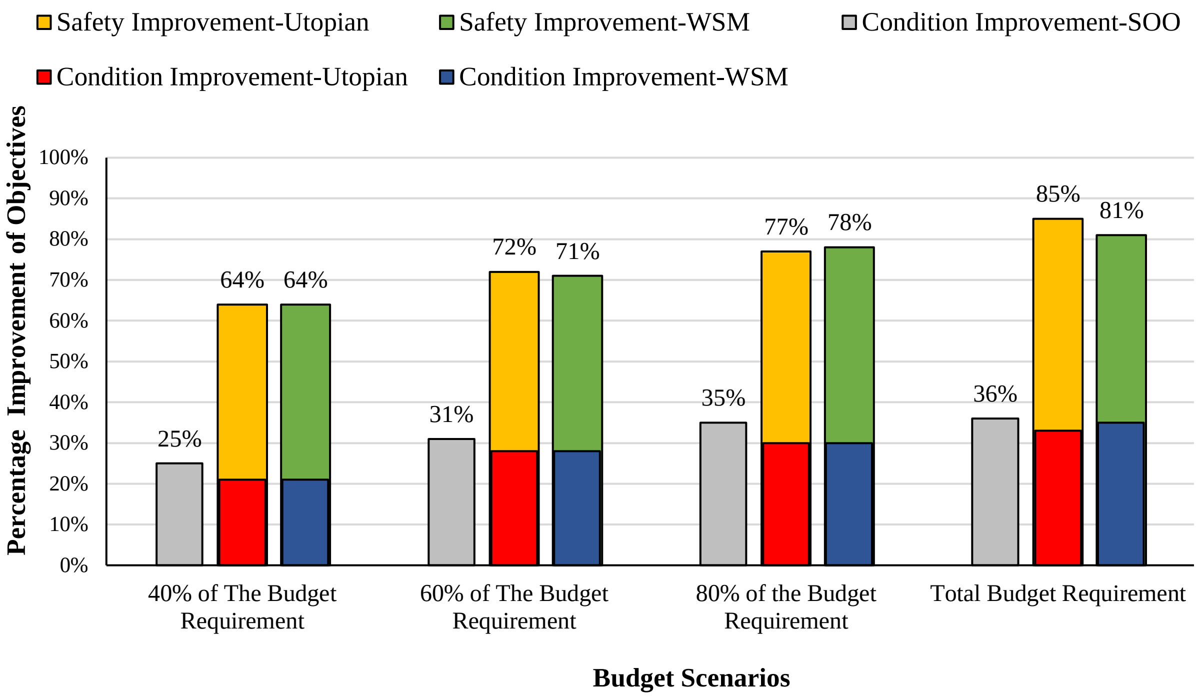

Figure 5-10: The Comparison of Condition and Safety Improvement between SOO Approach and MOO Approach

Mathematically, each Pareto optimal point can be equally acceptable for a multi-objective problem. However, in practice, it is desirable to obtain one solution/ M&R program and for that DM preference should be involved. The analyst presented the Pareto optimal solution set to the DM and the DM is to select the best work program based on the road agency's policies.

5.6 Summary of the Chapter

Chapter five was focused on the development of decision-making tools to solve the multi-objective problem. In this study socio-economic importance was incorporated in the maintenance planning decision-making scheme by using it as an objective function. For that, a socio-economic PI was proposed by using the priority factors; traffic volume, land use, community importance & accessibility to the road network. The attributes and weightages were defined based on the previous studies and the maximum attainable value for the PI is 100.

Next, a case study was conducted to evaluate the applicability of the proposed framework. It was identified a set of priority roads based on the PI score and the secondary objective was formulated as minimization of average priority road IRI. From the running optimization model, a set of Pareto optimal solutions were generated. Two methods have been proposed to select the best solution among the Pareto solutions namely the Utopian method and WSM. It was found that the Utopian method has been provided a better solution than WSM. However, WSM (0.5,0.5) scenario can be adopted in selecting the maintenance program. Anyway, the DM can select another solution based on his preference if not satisfied with these two methods.

Furthermore, another case study was conducted by incorporating safety performance in decision criteria using a predefined parameter called CSI. The results were found as in the previous case by generating a more distributed Pareto front. Since the same parameter was used in both objectives in the previous case study, the Pareto front becomes narrowed a bit while when used different parameters Pareto front becomes more spread.

The study has also shown that rather than spending money on optimizing a single objective, optimization of multiple objectives at a time would be a better option since the improvement of the existing network is higher as shown in Figure 5-10.

6 CONCLUSION

It was understood that LVRRs play a pivotal role in the rural community by providing connectivity to access markets, education and social needs. Lack of funding, technical knowledge and limited resources has resulted in local road agencies to difficulties in using conventional PMSs. Therefore, the subjective decision-making used by them caused resource wasting. To cater to these problems, the study proposed cost-effective condition evaluation criteria and simple analysis tools, but still, it should be able to provide the optimum maintenance program.

Smartphone-based IRI along with key distress types was proposed as the pavement condition evaluation method for LVRRs. To validate that, Roadroid IRI was compared with the Bump Integrator which is a Class III type roughness measurement equipment. The R-squared value between the two measurements was found as 0.78. Even though the relationship has shown that smartphone roughness slightly underestimates road roughness, still it can apply to LVRRs due to the cost-effectiveness, repeatability and easiness to use.

Moreover, the ability of roughness to predict the pavement distress conditions was assessed from the regression analysis between IRI and key distresses. It was found that Raveling, Edge Breaking, Pothole, Edge Gap, Pothole, Edge Breaking, Edge Gap has shown a good correlation with IRI as 0.61, 0.56, 0.55 & 0.52 respectively while cracking and patching were not provided a good correlation. The combined effect of distress on IRI progression was evaluated by multiple-regression analysis for narrow roads and wider roads respectively and the models had an R-squared of 0.86 while pothole representing the dominant distress type. In wider roads the effect of the edge breaking and edge gap on IRI progression is negligible hence omitted by stratified sampling. In that model, the existing patching sections were reduced the pavement roughness. Overall, the results were shown that roughness can capture key distress accurately. Therefore, it can be concluded that instead of time-consuming, tedious distress surveys, roughness would be a better alternative to evaluate pavement conditions in LVRRs.

Further, IRI progression was evaluated with the PCI and a non-linear relationship was found with an R-squared of 0.75 using the sigmoidal function. The model represents the whole range of pavement life with IRI varies from 2 m/km – 11 m/km. The categorization was done between predefined IRI and PCI ranges, the results show that the extreme conditions were similarly represented from the two indices. In addition to the PCI index PSR is compared with the IRI by calculating the model parameters, and it was found that R-squared of 0.76 in the developed model. That provides sufficient evidence of the capability of IRI to assess overall pavement condition for network-level planning purposes. Also, it was identified the different strategies and maintenance operation types used in Sri Lanka as well as the IRI intervention levels. From the collected data, a cost estimation model for major distresses from existing IRI values was developed. It was shown a strong predictive model with an R-squared of 0.9.

The decision-making tools were developed to maximize the network condition. For that purpose, an objective function was formulated to minimize average network IRI with the decision tree which induced project prioritization. Out of the two problem-solving systems, the GA-based method provided the optimum work program in both case studies. However, Integer Programming is also suitable for a small road network with simple decision-making criteria. Engineering objective decision-making would not be beneficial especially when there is a significant budgetary deficiency. However, in the situation where sufficient finding is available Engineering objective decision making can provide a better solution rather than in limited budget situations. Interestingly, the heuristic nature of the GA was helped to render near or optimal solutions even for a larger road network. Therefore, GA can be recommended to use to get the optimum work program for the LVRR network.

Finally, the PMS is focused on solving multi-objective problems. In that, socio-economic importance was incorporated in the maintenance planning decision-making scheme by use as an objective function. For that, a socio-economic PI was proposed by using the priority factors; traffic volume, land use, community importance & accessibility to the road network. The PI was helpful to identify the priority roads and the case study proved that use priority roads in the objective function would improve the priority road condition in addition to improving the overall network condition. Moreover, From the running optimization model, a set of Pareto optimal solutions were generated. Two methods have been proposed to select the best solution among the Pareto solutions namely the Utopian method and WSM. It was found that the Utopian method has been provided a better solution over WSM. However, WSM (0.5,0.5) scenario can be adopted in some situations. Anyway, the Utopian method would be the best option as shown in the study results. Furthermore, results from the case study conducted by incorporating safety performance in decision criteria generated a more distributed Pareto front. The study has also shown that rather than spending money on optimizing a single objective, optimization of multiple objectives at a time would be a better approach since the improvement of the existing network is higher in that sense.

The proposed PMS for LVRRs would reduce the data requirements, simplified the analytical tools and allowed users to customize considering the resource constraints. The prioritization and optimization models would allow road agencies to make objective decisions and optimize the road maintenance process. The finding from this research can be used for maintenance planning for local road authorities in Sri Lanka as well as for other developing countries by adopting the parameter defining for their local context.

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Appendix-A: Data Collection for Proposed Pavement Condition Criteria

Table A-1: Summary of Inventory & Condition Data of Selected Road Network for the Study

Name of the Road Link	Measured Length (km)	Average Width (m)	IRI (m/km)	ADT (veh/ day)	Pothole %	Raveling (%)	Cracking (%)	Patching (%)	Edge gap (%)	Edge break (%)	PCI (ASTM)
Hatharaman pasman Junction	1.3	5.67	2.40	38	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Amuna Junction - Maithreegama Road	4.0	3.63	1.76	70	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Piyapala Mawatha	9.6	3.62	1.67	126	0.00	0.00	0.00	0.00	0.00	0.01	**100**
Diya Bediya Road	9.6	3.78	1.38	151	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Opatha - Omatta - Bulugaha Road	5.0	3.71	1.56	151	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Goluwamulla Atakohota Road	3.6	4.17	1.66	176	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Kaluwalagoda Road	5.1	3.0	1.66	180	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Mada Kumbura junction Kaluwalagoda	4.6	2.43	1.75	182	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Bogaha junction kaluwalagoda road	1.9	3.12	1.75	192	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Amuna Junction - Maithreegama Road	2.0	2.72	2.50	192	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Dudley Senanayake Mawatha Weragoda	1.0	3.03	2.03	195	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Manampitiya - Dehigaha Bedda Kirindiela Road	2.7	2.78	1.52	263	0.00	0.00	0.00	0.00	0.00	0.00	**100**

Name of the Road Link	Measured Length (km)	Average Width (m)	IRI (m/km)	ADT (veh/ day)	Pothole %	Raveling (%)	Cracking (%)	Patching (%)	Edge gap (%)	Edge break (%)	PCI (ASTM)
Welibokkuwa - Banwelgodalla Road	0.9	3.07	1.63	266	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Ampegama school - Unapandura Junction Road	1.4	5.88	2.29	267	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Ibbawala - Panchaliya - Andugoda Road	1.0	3.23	2.19	268	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Ibbawala Ranamaduragama Road	2.3	2.61	2.44	268	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Sri sudarshi pirivena Mawatha	3.7	4.53	3.76	279	0.00	0.00	0.00	0.00	0.00	0.00	**100**
Okandayaya Paluwatta Road	1.5	3.13	2.64	280	0.00	0.00	0.00	0.00	0.00	0.00	**100**
NN - 01	2.1	3.13	1.76	281	0.00	0.00	0.00	0.00	0.00	0.00	**100**
NN - 02	5.0	4.68	2.02	282	0.00	0.00	0.00	0.00	0.00	0.00	**100**
NN - 03	2.8	5.7	3.69	287	0.00	0.17	0.17	0.00	0.00	0.00	**95**
Buddajayanthi Mawatha Thirangama Road	1.3	2.87	2.19	287	0.00	0.00	0.00	0.00	0.00	0.12	**92**
Mayakaduwa - Wadiyakanda - Makaduwa Temple	5.2	3.83	3.63	374	0.00	0.00	0.00	0.00	0.00	0.12	**92**
Madakumbura road	1.2	2.89	1.99	388	0.00	0.00	0.00	0.00	0.00	0.23	**91**
NN - 04	1.1	2.71	3.05	397	0.00	0.28	0.00	0.00	0.00	0.00	**91**
Wackwella - Ginimallagaha Road	7.5	2.67	1.95	401	0.00	0.00	0.00	0.00	0.00	0.36	**90**
10th Mile Post - Hakmana Gedara Kade	3.4	2.90	2.93	404	0.00	0.00	0.00	0.00	0.00	0.43	**89**

Name of the Road Link	Measured Length (km)	Average Width (m)	IRI (m/km)	ADT (veh/ day)	Pothole %	Raveling (%)	Cracking (%)	Patching (%)	Edge gap (%)	Edge break (%)	PCI (ASTM)
Mavita DuliElla (Mawita Kosmulla)	6.2	2.69	2.88	416	0.00	0.00	0.00	0.00	0.00	0.41	**89**
Hapugala - Eriyagaha Junction	3.0	2.78	2.23	457	0.00	0.00	0.00	0.00	0.00	0.59	**88**
Alapaladeniya - Thlpekumbura	2.5	2.62	2.90	460	0.00	0.00	0.00	0.00	0.00	0.57	**88**
Sri Piyarathna Mawatha (Kakuluwangoda Mawatha)	1.9	2.72	3.35	596	0.00	0.00	0.00	0.00	0.00	0.74	**87**
Kabaragala Badipita Puswelkada Unagaswita Galpoththa Kombala Junior School 10th mile post thiyabarahena Road	7.0	2.75	3.51	604	0.00	0.00	0.00	0.00	0.00	0.73	**87**
Thumbe - Kongala Road	4.7	2.64	2.35	606	0.00	0.00	0.00	0.00	0.00	0.78	**86**
Dangala - Dellawa Road	2.4	2.74	2.88	615	0.00	0.00	0.00	0.00	0.00	0.85	**86**
Hiyare East - School Road via Kaluwala Badipita Hawpe	1.2	2.80	6.55	619	0.00	0.00	0.00	0.00	0.00	1.04	**85**
Weliwa Pahuruthota - Neel Ella	4.5	2.92	2.80	624	0.00	0.00	0.00	0.00	0.00	1.00	**85**
Kapuhempala, Ambalamakanda, Hinidumgoda, Haliwala	1.8	3.07	2.85	629	0.00	0.00	0.00	0.00	0.00	1.12	**84**
Morawaka - Millawa	2.9	3.97	2.26	766	0.00	0.00	0.00	0.00	0.00	1.30	**83**
Nindana school to 5th mile post via Wathurawila	2.8	3.70	2.24	780	0.00	0.00	0.00	0.00	0.00	1.42	**82**

Name of the Road Link	Measured Length (km)	Average Width (m)	IRI (m/km)	ADT (veh/ day)	Pothole %	Raveling (%)	Cracking (%)	Patching (%)	Edge gap (%)	Edge break (%)	PCI (ASTM)
Nagashandiya - Halpathota Road	1.2	4.60	2.28	788	0.00	0.00	0.00	0.00	0.00	1.55	**82**
Kadurupokuna - Seenimodara Road	2.5	3.76	2.61	793	0.00	0.00	0.00	0.00	0.00	1.45	**82**
Danawala Mawita Road	3.7	3.44	2.73	798	0.00	0.00	0.00	0.00	0.00	1.73	**81**
Poramba School diyalape junction Road	3.7	3.14	3.45	830	0.00	0.00	1.20	0.00	0.00	0.55	**81**
Berala Panathara - Thala Palakanda	6.0	2.82	2.68	835	0.00	0.00	0.00	0.00	0.00	2.16	**81**
Surasena Mawatha	1.7	2.75	2.20	837	0.00	0.00	2.94	0.00	0.00	0.04	**80**
Sulthanagoda welihinna	1.5	2.74	2.78	889	0.00	0.00	1.58	0.00	0.00	0.42	**80**
Dewagoda - Balabokka Road	0.7	2.5	1.89	902	0.00	0.00	0.00	0.00	0.00	2.02	**80**
Galkatiya Jayasumanarama goviyapana Road	1.5	2.6	2.34	912	0.00	0.00	0.00	0.00	0.00	2.23	**80**
Weeravila Ara 01st Cross Road	1.2	2.7	2.58	1046	0.00	0.00	2.85	0.00	0.00	0.04	**80**
Galduwa Aranya Road	2.3	2.62	1.56	1067	0.00	0.00	0.00	0.00	0.00	2.50	**78**
Kongala D. C. Abeywuckrama Road	2.4	2.8	2.36	1119	0.00	0.00	3.77	0.00	0.00	0.13	**78**
kiriwalladolaJunctToHingurahena	2.0	2.7	3.27	1131	0.00	0.00	1.11	0.00	0.00	1.19	**78**
K.G.Palis Mawatha	2.0	2.6	2.02	1145	0.00	0.00	0.00	0.00	0.00	2.90	**77**
Porupitiya - Annasigalawila Road	1.4	3.12	2.67	1157	0.00	0.00	0.00	0.00	0.00	2.86	**77**

Name of the Road Link	Measured Length (km)	Average Width (m)	IRI (m/km)	ADT (veh/ day)	Pothole %	Raveling (%)	Cracking (%)	Patching (%)	Edge gap (%)	Edge break (%)	PCI (ASTM)
Denuwala - Kapuwatta Jaya Wijayagama Road	1.0	3.08	2.31	1158	0.00	0.00	6.05	0.00	0.00	0.07	**76**
Dodampe Padinnoruwa Road	2.8	3.37	1.86	1169	0.00	0.00	0.00	0.00	0.00	3.36	**76**
Waulagala Batakatiya Road	2.1	2.82	2.30	1182	0.00	0.00	0.00	0.00	0.00	3.54	**75**
Bataduwa - Sudarmaramaya Road	1.0	2.83	2.48	1182	0.00	0.00	0.00	0.00	0.00	3.74	**75**
Ela Banteka Para	3.6	2.75	6.54	1213	0.00	0.00	0.00	1.79	0.00	0.00	**74**
Morawaka - Paragala Diyadawa Road	11.2	2.85	3.14	1235	0.00	0.00	1.40	0.00	0.00	2.26	**73**
NN - 05	4.0	3.03	10.78	1263	0.00	5.15	0.21	0.07	0.00	0.00	**71**
Kahawa - Galduwa Road	1.9	3.04	1.64	1277	0.00	0.00	0.00	0.00	0.00	5.75	**70**
Sirikadura Watta Sunami Niwasa Road	1.5	2.97	3.26	1342	0.00	0.00	0.00	0.00	0.00	5.73	**70**
Boosa Hegoda Rajakoratuwa Road	1.2	6.45	2.32	1347	0.00	0.00	0.00	1.28	0.00	1.39	**69**
Kadigamuwa - Palamkada Road	5.5	3.21	2.95	1348	0.00	0.00	2.20	1.52	0.00	0.00	**69**
NN - 06	3.7	4.83	6.34	1369	0.00	1.47	0.60	0.40	2.26	0.00	**69**
Uswewa via Pahalagama sooriya pokuna junction	6.3	6.5	2.09	1383	0.00	0.00	1.61	0.00	0.00	4.20	**68**
NN - 07	5.0	5.7	7.21	1440	0.00	29.95	0.20	0.05	0.00	0.00	**68**
NN - 08	3.0	4.17	5.82	1488	0.00	8.64	0.35	0.00	0.14	0.00	**68**
NN - 09	2.0	3.23	7.26	1507	0.06	8.65	0.07	0.02	0.00	0.00	**65**
NN - 10	5.0	3.7	6.43	1513	0.00	9.40	0.77	0.00	0.00	0.00	**63**
NN - 11	2.5	4.22	3.20	1531	0.00	6.44	0.00	0.00	0.00	0.00	**61**

Name of the Road Link	Measured Length (km)	Average Width (m)	IRI (m/km)	ADT (veh/ day)	Pothole %	Raveling (%)	Cracking (%)	Patching (%)	Edge gap (%)	Edge break (%)	PCI (ASTM)
NN - 12	1.6	3.97	6.20	1548	0.00	14.10	0.59	0.74	0.43	0.00	**61**
NN - 13	2.4	3.48	12.22	1611	0.00	20.62	0.86	0.36	0.00	0.00	**61**
NN - 14	2.3	2.89	6.39	1613	0.00	57.01	4.21	0.02	0.00	0.00	**58**
NN - 15	1.8	4.18	8.32	1629	0.00	29.34	0.00	0.00	0.00	0.00	**56**
NN - 16	2.7	4.33	11.30	1682	0.00	34.89	0.00	0.00	0.00	0.00	**55**
NN - 17	1.7	6.18	9.59	1742	0.00	25.74	0.00	0.00	0.00	0.00	**55**
NN - 18	1.8	2.95	6.30	1767	0.00	28.55	0.00	0.00	0.00	0.00	**55**
NN - 19	4.0	3.12	7.59	1789	0.03	4.67	1.21	0.12	0.00	0.00	**53**
NN - 20	2.5	3.20	7.87	1794	0.00	12.51	2.61	2.54	1.68	0.00	**48**
NN - 21	2.2	2.89	10.67	1802	0.00	14.96	11.25	0.67	1.29	0.00	**48**
NN - 22	3.2	3.13	11.33	1803	0.00	11.21	13.01	0.64	2.86	0.00	**46**
NN - 23	2.0	6.19	5.21	1824	0.05	6.64	0.94	1.58	0.00	0.00	**44**
NN - 24	2.0	3.01	9.58	1858	0.16	21.34	0.44	0.44	7.14	0.00	**44**
NN - 25	1.0	2.87	9.36	1897	0.00	31.22	0.40	4.48	5.75	0.00	**44**
NN - 26	1.6	2.83	9.44	1901	0.00	8.56	4.84	2.03	9.35	0.00	**38**
NN - 27	3.5	2.96	10.56	1933	0.34	42.43	0.00	0.00	0.00	0.00	**31**
NN - 28	2.3	5.62	11.69	1967	0.44	55.34	2.93	3.10	1.66	0.00	**29**
NN - 29	3.0	3.38	8.77	2033	0.06	7.44	0.93	0.18	7.25	0.00	**25**
NN - 30	4.0	3.11	9.58	2060	0.15	10.95	11.39	0.00	0.13	0.00	**24**
NN - 31	2.7	2.70	13.50	2090	0.29	36.60	4.42	0.01	8.66	0.00	**23**
NN - 32	2.5	2.64	9.79	2135	0.17	23.75	16.59	4.99	0.00	0.00	**20**
NN - 33	4.0	5.36	11.41	2138	0.23	28.31	3.72	2.23	13.81	0.00	**15**
NN - 34	4.0	2.77	10.54	2213	0.06	8.89	6.37	0.48	3.32	11.99	**9**

*NN – No Name, ADT – Average Daily Traffic, IRI – International Roughness Index, PCI – Pavement Condition Index

Table A-2: Calibration Sheet of Bump Integrator

Date:		**Reference IRI Device**	**Recommended Reference IRI Range**	
Vehicle ID:	Passenger car	**Date Reference IRI Collected**	**One site < 3 IRI**	Pass
Mileage:		**Reference IRI Device**	**Three Sites 3 < 6 IRI**	Pass
Operator:	Kelum	*if "Other" Enter Device Name*	**One Site > 6 IRI**	Pass

Calibration Site Number	**Reference IRI (m/km)**	**Site Length (m)**	**Calibration Speed (km/h)**	**ROMDAS Raw BI Count**			**Number of Runs**	**Run Mean Raw BI Count**	**Raw BI count/km**	**Pass/Fail 90%**	**Pass/Fail 95%**	**Calibration Coefficients Roughness**		
				Run Number								**Roughness = a2 x BI + a1**		
				1	**2**	**3**						**A2**	**A1**	**R^2**
1	1.71	400	30	1149	1338	1338	3	1275	3188	Pass	Pass	0.0004187	0.8519	0.9848
2	3.57	300	30	1843	1989	1725	3	1852	6174	Pass	Pass		Pass	Pass
3	4.10	400	30	2993	3329	2993	3	3105	7763	Pass	Pass			
4	4.80	400	30	3052	3299	3506	3	3286	8214	Pass	Pass			
5	9.62	300	30	6286	6584	6324	3	6398	21327	Pass	Pass			
1	1.71	400	50	1482	1439	1575	3	1499	3747	Pass	Pass	0.0003998	0.4216	0.9922
2	3.57	300	50	2328	2428	2328	3	2361	7871	Pass	Pass		Pass	Pass
3	4.10	400	50	3938	3722	3801	3	3820	9551	Pass	Pass			
4	4.80	400	50	3900	3984	3921	3	3935	9838	Pass	Pass			
5	9.62	300	50	6786	6715	7427	3	6976	23253	Pass	Pass			

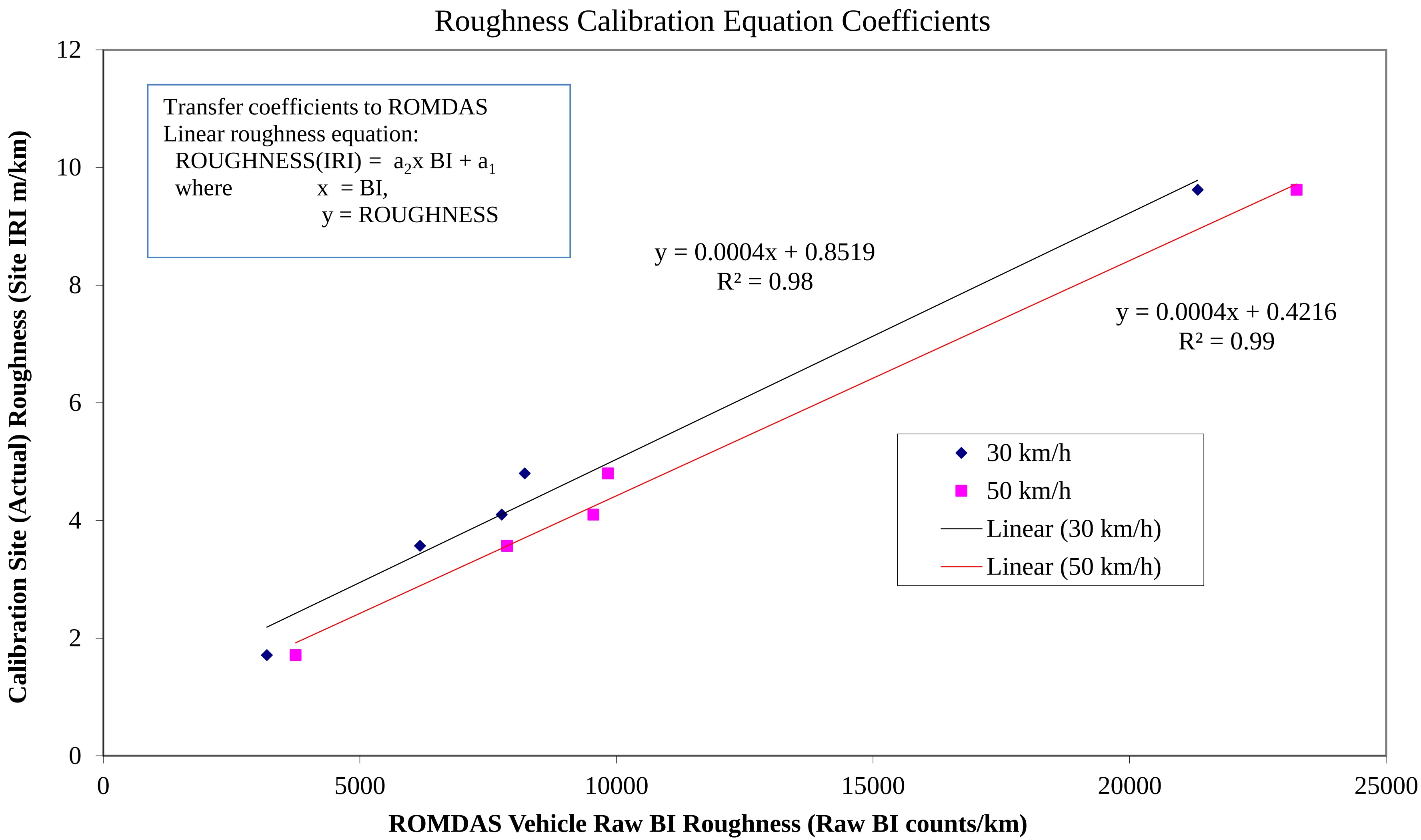

Figure A-1: Bump Integrator Calibration Graph for the Speed

Table A-3: A Sample Data Sheet Extracted from Roadroid Mobile Application

Import Date	Username	Unit Name	Import Status	Avg eIRI	Avg cIRI	Avg Speed	Road ID	Survey Length (m)	Type
21/3/2019	UniMoratuwa01	Kelum1	Import OK	1.92	3.97	39.56	166	1595	Road Condition
21/3/2019	UniMoratuwa01	Kelum1	Import OK	2.28	5.15	32.02	165	1995	Road Condition
21/3/2019	UniMoratuwa01	Kelum1	Import OK	1.97	3.41	31.05	164	2246	Road Condition
21/3/2019	UniMoratuwa01	Kelum1	Import OK	6.33	5.41	23.67	163	2063	Road Condition
21/3/2019	UniMoratuwa01	Kelum1	Import OK	2.08	3.04	33.97	162	1270	Road Condition
21/3/2019	UniMoratuwa01	Kelum1	Import OK	9.11	3.27	26.66	161	1694	Road Condition
21/3/2019	UniMoratuwa01	Kelum1	Import OK	1.95	3.31	30.11	160	1312	Road Condition
21/3/2019	UniMoratuwa01	Kelum1	Import OK	1.76	3.36	39.35	159	2702	Road Condition

Table A-4: Roughness Value from Bump Integrator and Roadroid Mobile App

No	Road Name	Measured Length (km)	Bump Integrator Average IRI (m/km)	Roadroid IRI (m/km)
1	Thannahengoda Road	2.0	2.85	1.66
2	Hatharaman Pasman Junction	1.3	2.40	1.62
3	Amuna Junction-Maithreegama Road	4.0	1.76	1.56
4	Elpitiya Awittawa LHS - start ch near bridge	9.6	1.67	1.58
5	Elpitiya Awittawa RHS	9.6	1.38	1.62
6	Opatha - Omatta - Bulugaha Road	5.0	1.56	1.66
7	Goluwamulla Atakohota Road	3.6	1.66	1.65
8	Kaluwalagoda Road	5.1	1.66	1.55
9	Mada Kumbura junction Kaluwalagoda Road	4.6	1.75	1.63
10	Bogaha junction kaluwalagoda road	1.9	1.75	1.54
11	Amuna Junction-Maithreegama Road	2.0	2.50	2.56
12	Surasena Mawatha	2.0	2.20	2.13
13	Galduwa Aranya Road	2.3	1.56	1.55
14	Kahawa - Galduwa Road	1.9	1.64	1.47
15	Dudley Senanayake Mawatha Weragoda	1.0	2.03	1.31
16	Nindana school to 5th-milepost via Wathurawila	2.8	2.24	1.69
17	Manampitiya - Dehigaha Bedda Kirindiela Road	2.7	1.52	1.54
18	Welibokkuwa - Banwelgodalla Rd	0.9	1.63	1.53
19	Ampegama school - Unapandura Junction Road	1.4	2.29	1.44
20	Nagashandiya - Halpathota Road	1.2	2.28	1.54
21	Waulagala Batakatiya	2.1	2.30	1.67
22	Buddajayanthi Mawatha Thirangama Road	1.3	2.19	1.52
23	Sirikadura Watta Sunami Niwasa Rd	1.5	3.26	1.77
24	K.G.Palis Mawatha	2.0	2.02	1.47
25	Wackwella - Ginimallagaha	7.5	1.95	1.70
26	Boosa Hegoda Rajakoratuwa Road	1.2	2.32	1.48
27	Denuwala - Kapuwatta Jaya Wijayagama	1.0	2.31	2.12
28	Ibbawala - Panchaliya - Andugoda	1.0	2.19	1.83
29	Ibbawala Ranamaduragama Rd	2.3	2.44	2.18
30	Kongala D. C. Abeywuckrama Road	2.4	2.36	2.21
31	Sulthanagoda welihinna	1.5	2.78	1.70

No	Road Name	Measured Length (km)	Bump Integrator Average IRI (m/km)	Roadroid IRI (m/km)
32	Thumbe - Kongala Road	4.7	2.35	2.10
33	10th Mile Post - Hakmana Gedara Kade	3.4	2.93	2.38
34	Sri Piyarathna Mawatha (Kakuluwangoda Mawatha)	1.9	3.35	2.43
35	Sri sudarshi pirivena to bibu	3.7	3.76	2.47
36	Madakumbura road	1.2	1.99	1.55
37	Dewagoda - Balabokka Rd	0.7	1.89	1.64
38	Hapugala - Eriyagaha Junction	3.0	2.23	1.64
39	Kabaragala Badipita Puswelkada Unagaswita Galpoththa Kombala Junior School 10th milepost thiyabarahena Rd	7.0	3.51	2.72
40	Hiyare East - School Road via Kaluwala Badipita Hawpe	1.2	6.55	3.12
41	Dodampe Padinnoruwa	2.8	1.86	2.08
42	Kapuhempala, Ambalamakanda, Hinidumgoda, Haliwala	1.8	2.85	1.87
43	Danawala Mawita	3.7	2.73	1.90
44	Mavita DuliElla (Mawita Kosmulla)	6.2	2.88	2.04
45	Dangala - Dellawa	2.4	2.88	2.19
46	Bataduwa - Sudarmaramaya Rd	1.0	2.48	2.05
47	Galkatiya Jayasumanarama goviya	1.5	2.34	1.89
48	poramba school diyalape junc vi	3.7	3.45	2.97
49	Morawaka - Paragala Diyadawa	11.2	3.14	2.84
50	Porupitiya - Annasigalawila	1.4	2.67	2.29
51	Morawaka - Millawa	2.9	2.26	2.02
52	Alapaladeniya - Thlpekumbura	2.5	2.90	2.33
53	Weliwa Pahuruthota - Neel Ella	4.5	2.80	2.31
54	Kadigamuwa - Palamkada	5.5	2.95	2.51
55	Ela Banteka Para	3.6	6.54	4.76
56	Okandayaya Paluwatta Rd	1.5	2.64	2.32
57	Uswewa via Pahalagama sooriya pokuna junction	6.3	2.09	1.99
58	Kadurupokuna - Seenimodara road	2.5	2.61	1.93
59	Weeravila Ara 01st Cross Road	1.2	2.58	2.62
60	Kiriwalladola Junction To Hingurahena	2.0	3.27	2.18
61	Berala Panathara - Thala Palakanda	6.0	2.68	2.15
62	Jamburegoda- Bodhirukkaramaya	1.7	4.66	3.19
63	Mayakaduwa Wadiyakanda Makaduwa Temple	4.2	3.73	3.15

No	Road Name	Measured Length (km)	Bump Integrator Average IRI (m/km)	Roadroid IRI (m/km)
64	Mayakaduwa Kombala Temple Watiyadeniya Heenpandala	0.9	3.63	3.12
65	Udukawa Badurawila	1.3	4.97	3.55
66	Ogaspe junction to Maligathenna Aththudawa road	0.7	8.92	9.42
67	Agawaththa Thalgahagoda for Jayawardhana	1.1	2.83	3.78
68	Pahattu kade to nagoda via welihinda junction	0.9	4.60	4.82
69	Katavila Sulthanagoda Road	0.4	10.07	6.13
70	Baragammulla Moragasmandiya	1.8	7.01	5.78
71	Gonadenihena kanda via rajapaksha mawatha	0.4	6.42	4.01
72	Sumihirigama co-op city	1.9	2.49	1.78
73	Gajanayaka debokkawa junction Gajanayakagama junction	1.9	4.47	3.67
74	School to ela banteka para	0.9	4.75	3.51
75	Upasakagoda well water tank	1.2	3.67	3.46
76	Warapitiya hospital to Karadeniya	0.4	3.68	3.17
77	Urubokka Pothdeniya Road	2.7	3.30	3.05
78	kolawenigama uggalpotha	1.6	2.96	4.55

Table A-5: Road Details and Estimated IRI Values for Narrow Roads Multiple Regression Model Validation

Road Name	Average Width (m)	Section ID	POT %	RAV %	CRA %	EDB %	EDG %	Estimated IRI (m/km)	Measured IRI (m/km)
Uduwelwala Hamathanna Road	3.0	1	0.14	10.00	10.00	5.00	0.00	8.75	6.10
	3.0	2	0.30	0.00	5.00	2.00	0.00	7.21	8.40
Nippon Bridge road to Namini Village	3.6	1	0.16	10.00	10.00	10.00	0.00	9.74	7.40
	3.0	3	0.16	7.00	7.00	5.00	0.00	7.65	10.10
	3.0	4	0.16	10.00	7.00	5.00	0.00	7.92	6.95
	3.0	5	0.16	10.00	10.00	5.00	0.00	8.94	9.20
	3.0	2	0.12	0.00	0.00	10.00	0.00	5.05	6.57
Road from 2nd mile post, Walgamwewa to Athubediyawa watta junction	3.0	1	0.00	5.00	10.00	5.00	0.00	6.95	5.60
	3.0	2	0.30	25.00	10.00	10.00	0.00	12.44	11.00
	3.0	3	0.00	10.00	5.00	5.00	0.00	5.70	3.60
	3.0	4	0.00	5.00	5.00	0.00	0.00	4.45	3.30
	3.0	5	0.00	31.22	0.40	0.00	5.75	8.64	9.36
	3.0	6	0.00	10.00	5.00	5.00	0.00	5.70	4.20
	3.0	7	0.30	25.00	10.00	10.00	0.00	12.44	10.97
	3.0	8	0.08	25.00	10.00	10.00	0.00	10.32	9.70
	3.0	9	0.00	10.00	5.00	0.00	0.00	4.90	6.30
	3.0	10	0.08	10.00	5.00	0.00	0.00	5.67	4.30
From A6 road to Amaya Lake hotel via National Youth Corps and block 40	3.2	1	0.00	10.00	5.00	0.00	0.00	4.90	3.60
	3.2	2	0.08	10.00	15.00	10.00	0.00	10.67	10.40
	3.2	3	0.06	7.44	0.93	0.00	7.25	5.02	4.90
	3.2	4	0.08	10.00	15.00	10.00	0.00	10.67	10.80
	3.2	5	0.00	5.00	5.00	0.00	0.00	4.45	3.34
Demodaya middle road	3.0	1	0.00	5.00	5.00	0.00	0.00	4.45	4.00
	3.0	2	0.24	5.00	10.00	5.00	0.00	9.26	10.8
Pabahinna Kinchigune road	3.0	1	0.00	5.00	5.00	0.00	0.00	4.45	4.50
Road from Nabadagaswewa to Kanadarawa 5 Ela Cemetry	4.0	1	0.06	30.30	0.00	2.27	0.00	5.97	5.30
Willpattu road from Lidawewa in Puttalam Anuradhapura road via Rukadawewa	4.0	1	0.01	35.00	0.00	2.50	0.00	5.93	6.10
Road from Mihinthalaya Welankulama Junction to	3.8	1	0.30	35.00	0.00	7.89	0.00	9.60	7.70

Bogahyaya Village									
Road to Kirinda Hospital from Kirinda Jumma Mosque	3.7	1	0.30	30.00	0.00	19.43	0.00	10.99	9.00
Padikemgala Temple Road	3.0	1	0.35	35.00	0.00	10.00	0.00	10.41	9.60
Road to Beragama Hospital from Bellagaswewa junction	3.6	1	0.40	0.97	0.00	2.50	0.00	6.64	5.20
	3.6	2	0.00	0.00	1.02	6.67	0.00	3.71	4.20

Table A-6: The Road Prioritization Ranking in IRI and PCI Basis

No	Road Name	IRI (m/km)	PCI (ASTM)	Rank IRI	Rank PCI	d^2
1	Hatharaman pasman Junction	2.40	100	36	1	1225
2	Amuna Junction - Maithreegama Road	1.76	100	12	1	121
3	Piyapala Mawatha	1.67	100	9	1	64
4	Diya Bediya Road	1.38	100	1	1	0
5	Opatha - Omatta - Bulugaha Road	1.56	100	3	1	4
6	Goluwamulla Atakohota Road	1.66	100	7	1	36
7	Kaluwalagoda Road	1.66	100	7	1	36
8	Mada Kumbura junction Kaluwalagoda	1.75	100	10	1	81
9	Bogaha junction kaluwalagoda road	1.75	100	10	1	81
10	Amuna Junction - Maithreegama Road	2.50	100	39	1	1444
11	Dudley Senanayake Mawatha Weragoda	2.03	100	20	1	361
12	Manampitiya - Dehigaha Bedda Kirindiela Road	1.52	100	2	1	1
13	Welibokkuwa - Banwelgodalla Rd	1.63	100	5	1	16
14	Ampegama school - Unapandura Junction Road	2.29	100	29	1	784
15	Ibbawala - Panchaliya - Andugoda	2.19	100	22	1	441
16	Ibbawala Ranamaduragama Rd	2.44	100	37	1	1296
17	Sri sudarshi pirivena to bibu	3.76	100	64	1	3969
18	Okandayaya Paluwatta Rd	2.64	100	42	1	1681
19	NA - 01	1.76	100	12	1	121
20	NA - 02	2.02	100	18	1	289
21	NA - 03	3.69	95	63	21	1764
22	Buddajayanthi Mawatha Thirangama Road	2.19	92	22	22	0
23	Mayakaduwa - Wadiyakanda, Makaduwa Temple	3.63	92	62	22	1600
24	Madakumbura road	1.99	91	17	24	49
25	NA - 04	3.05	91	54	24	900
26	Wackwella - Ginimallagaha	1.95	90	16	26	100
27	10th Mile Post - Hakmana Gedara Kade	2.93	89	52	27	625

No	Road Name	IRI (m/km)	PCI (ASTM)	Rank IRI	Rank PCI	d^2
28	Mavita DuliElla (Mawita Kosmulla)	2.88	89	49	27	484
29	Hapugala - Eriyagaha Junction	2.23	88	25	29	16
30	Alapaladeniya - Thlpekumbura	2.90	88	51	29	484
31	Sri Piyarathna Mawatha (Kakuluwangoda Mawatha)	3.35	87	59	31	784
32	Kabaragala Badipita Puswelkada Unagaswita Galpoththa Kombala Junior School 10th milepost thiyabarahena Rd	3.51	87	61	31	900
33	Thumbe - Kongala Road	2.35	86	34	33	1
34	Dangala - Dellawa	2.88	86	49	33	256
35	Hiyare East - School Road via Kaluwala Badipita Hawpe	6.55	85	73	35	1444
36	Weliwa Pahuruthota - Neel Ella	2.80	85	47	35	144
37	Kapuhempala, Ambalamakanda, Hinidumgoda, Haliwala	2.85	84	48	37	121
38	Morawaka - Millawa	2.26	83	27	38	121
39	Nindana school to 5th-mile post via Wathurawila	2.24	82	26	39	169
40	Nagashandiya - Halpathota Road	2.28	82	28	39	121
41	Kadurupokuna - Seenimodara road	2.61	82	41	39	4
42	Danawala Mawita	2.73	81	45	42	9
43	poramba school diyalape junc vi	3.45	81	60	42	324
44	Berala Panathara - Thala Palakanda	2.68	81	44	42	4
45	Surasena Mawatha	2.20	80	24	45	441
46	Sulthanagoda welihinna	2.78	80	46	45	1
47	Dewagoda - Balabokka Rd	1.89	80	15	45	900
48	Galkatiya Jayasumanarama goviya	2.34	80	33	45	144
49	Weeravila Ara 01st Cross Road	2.58	80	40	45	25
50	Galduwa Aranya Road	1.56	78	3	50	2209
51	Kongala D. C. Abeywuckrama Road	2.36	78	35	50	225
52	kiriwalladolaJunctToHingurahena	3.27	78	58	50	64
53	K.G.Palis Mawatha	2.02	77	18	53	1225
54	Porupitiya - Annasigalawila	2.67	77	43	53	100
55	Denuwala - Kapuwatta Jaya Wijayagama	2.31	76	31	55	576

No	Road Name	IRI (m/km)	PCI (ASTM)	Rank IRI	Rank PCI	d^2
56	Dodampe Padinnoruwa	1.86	76	14	55	1681
57	Waulagala Batakatiya	2.30	75	30	57	729
58	Bataduwa - Sudarmaramaya Rd	2.48	75	38	57	361
59	Ela Banteka Para	6.54	74	72	59	169
60	Morawaka - Paragala Diyadawa	3.14	73	55	60	25
61	NA - 05	10.78	71	89	61	784
62	Kahawa - Galduwa Road	1.64	70	6	62	3136
63	Sirikadura Watta Sunami Niwasa Rd	3.26	70	57	62	25
64	Boosa Hegoda Rajakoratuwa Road	2.32	69	32	64	1024
65	Kadigamuwa - Palamkada	2.95	69	53	64	121
66	NA - 06	6.34	69	69	64	25
67	Uswewa via Pahalagama sooriya pokuna junction	2.09	68	21	67	2116
68	NA - 07	7.21	68	74	67	49
69	NA - 08	5.82	68	66	67	1
70	NA - 09	7.26	65	75	70	25
71	NA - 10	6.43	63	71	71	0
72	NA - 11	3.20	61	56	72	256
73	NA - 12	6.20	61	67	72	25
74	NA - 13	12.22	61	94	72	484
75	NA - 14	6.39	58	70	75	25
76	NA - 15	8.32	56	78	76	4
77	NA - 16	11.30	55	90	77	169
78	NA - 17	9.59	55	84	77	49
79	NA - 18	6.30	55	68	77	81
80	NA - 19	7.59	53	76	80	16
81	NA - 20	7.87	48	77	81	16
82	NA - 21	10.67	48	88	81	49
83	NA - 22	11.33	46	91	83	64
84	NA - 23	5.21	44	65	84	361
85	NA - 24	9.58	44	83	84	1
86	NA - 25	9.36	44	80	84	16
87	NA - 26	9.44	38	81	87	36
88	NA - 27	10.56	31	87	88	1
89	NA - 28	11.69	29	93	89	16
90	NA - 29	8.77	25	79	90	121
91	NA - 30	9.58	24	82	91	81

No	Road Name	IRI (m/km)	PCI (ASTM)	Rank IRI	Rank PCI	d^2
92	NA - 31	13.50	23	95	92	9
93	NA - 32	9.79	20	85	93	64
94	NA - 33	11.41	15	92	94	4
95	NA - 34	10.54	9	86	95	81

Table A-7: Calculated Cost Values for Major Distress Repair Cost Estimation Model

Road Section Name	IRI (m/km)	Raveling (%)	Cracking (%)	Edge Breaking (%)	Cost per Sq. meter (Rs.)
Uswewa via Pahalagama sooriya pokuna junction	2.09	0.00	1.61	0.00	18.00
Surasena Mawatha	2.20	0.00	2.94	0.00	32.00
Denuwala - Kapuwatta Jaya Wijayagama	2.31	0.00	6.05	0.00	67.00
Kongala D. C. Abeywuckrama Road	2.36	0.00	3.77	0.00	41.00
Weeravila Ara 01st Cross Road	2.58	0.00	2.85	0.00	31.00
Sulthanagoda welihinna	2.78	0.00	1.58	0.00	17.00
Kadigamuwa - Palamkada	2.95	0.00	2.20	0.00	24.00
NN - 04	3.05	0.28	0.00	0.00	9.00
Morawaka - Paragala Diyadawa	3.14	0.00	1.40	0.00	15.00
NN - 11	3.20	6.44	0.00	0.00	206.00
Kiriwalladola Junction To Hingurahena	3.27	0.00	1.11	0.00	12.00
Poramba school diyalape junction	3.45	0.00	1.20	0.00	13.00
NA - 03	3.69	0.17	0.17	0.00	7.00
NN - 23	5.21	6.64	0.94	0.00	223.00
NN - 08	5.82	8.64	0.35	0.14	288.00
NN - 12	6.20	14.10	0.59	0.43	481.00
NN - 18	6.30	28.55	0.00	0.00	914.00
NA - 06	6.34	1.47	0.60	2.26	177.00
NN - 10	6.43	9.40	0.77	0.00	309.00
NN - 07	7.21	29.95	0.20	0.00	961.00
NN - 09	7.26	8.65	0.07	0.00	278.00
NN - 19	7.59	4.67	1.21	0.00	163.00
NN - 20	7.87	12.51	2.61	1.68	521.00
NN - 15	8.32	29.34	0.00	0.00	939.00
NN - 29	8.77	7.44	0.93	7.25	643.00
NN - 25	9.36	31.22	0.40	5.75	1,517.00
NN - 26	9.44	8.56	4.84	9.35	1,037.00
NN - 30	9.58	10.95	11.39	0.13	683.00
NN - 24	9.58	21.34	0.44	7.14	1,277.00
NN - 17	9.59	25.74	0.00	0.00	1,024.00
NN - 32	9.79	23.75	16.59	0.00	1,142.00
NN - 27	10.56	42.43	0.00	0.00	1,558.00

Road Section Name	IRI (m/km)	Raveling (%)	Cracking (%)	Edge Breaking (%)	Cost per Sq. meter (Rs.)
NN - 16	11.30	34.89	0.00	0.00	1,316.00
NN - 28	11.69	55.34	2.93	1.66	1,894.00
NN - 31	13.50	36.60	4.42	8.66	1,692.00

Appendix-B: Road Network Details for Single Objective Optimization Approach

Table B-1: Summary of Road Inventory for Rathnapura PRDA Road Network

Road Link Name	Existing IRI (m/km)	Pothole (Nos)	Length (km)	Width (m)
C002/Sec0001	5.2	0	1	3
C002/Sec0002	9.3	13	1	3
C003/Sec0001	5.7	0	1	3.5
C003/Sec0002	5.4	0	1	3.5
C004/Sec0001	3.1	1	1	3.5
C004/Sec0002	4.4	0	1	3.5
C005/Sec0001	2.7	3	1	3.2
C005/Sec0002	3.6	9	1	3.2
C008/Sec0001	2.5	4	1	3.5
C008/Sec0002	3.4	5	1	3.5
C300/Sec0001	6.4	14	1	3
C300/Sec0002	6.9	18	1	3
C300/Sec0003	7.8	14	1	3
C300/Sec0004	8.2	12	1	3
C301/Sec0001	6.3	8	1	3
C301/Sec0002	6.7	6	1	3
C301/Sec0003	9.2	35	1	3
C301/Sec0004	6.0	10	1	3
D002/Sec0001	5.3	6	1	3
D002/Sec0002	10.0	19	1	3
D002/Sec0003	6.1	5	1	3
D002/Sec0004	8.7	26	1	3.2
D004/Sec0001	2.9	0	1	3.2
D004/Sec0002	3.7	0	1	3.2
D005/Sec0001	6.1	4	1	3
D005/Sec0002	5.0	4	1	3
D005/Sec0003	11.0	29	1	3

Table B-2: Selected M&R Program under Rs.100 Million Budget Level using Integer Programming

Road Link Name	Existing IRI (m/km)	Pothole (Nos)	Selected Strategy	Post Condition IRI (m/km)	Project Cost (LKR)
C008/Sec0001	2.5	4	0	2.5	67,470
C005/Sec0001	2.7	3	0	2.7	67,470
D004/Sec0001	2.9	0	0	2.9	67,470
C004/Sec0001	3.1	1	0	3.1	67,470
C008/Sec0002	3.4	5	0	3.4	67,470
C005/Sec0002	3.6	9	0	3.6	67,470
D004/Sec0002	3.7	0	0	3.7	67,470
C004/Sec0002	4.4	0	1	3.9	179,671
D005/Sec0002	5.0	4	2	2.8	4,198,091
C002/Sec0001	5.2	0	2	2.8	4,234,167
D002/Sec0001	5.3	6	1	4.2	294,830
C003/Sec0002	5.4	0	2	2.8	4,979,101
C003/Sec0001	5.7	0	2	2.8	5,073,774
C301/Sec0004	6.0	10	2	3.0	4,463,435
D002/Sec0003	6.1	5	2	3.1	4,504,523
D005/Sec0001	6.1	4	1	4.5	544,523
C301/Sec0001	6.3	8	2	3.1	4,597,044
C300/Sec0001	6.4	14	2	3.2	4,648,841
C301/Sec0002	6.7	6	2	3.2	4,828,322
C300/Sec0002	6.9	18	1	4.6	1,009,270
C300/Sec0003	7.8	14	2	3.3	5,810,265
C300/Sec0004	8.2	12	2	3.3	6,260,692
D002/Sec0004	8.7	26	2	2.8	7,277,036
C301/Sec0003	9.2	35	2	3.0	7,334,588
C002/Sec0002	9.3	13	2	2.9	7,425,073
D002/Sec0002	10.0	19	2	3.1	7,937,098
D005/Sec0003	11.0	29	3	2.2	12,300,000

Selection Strategy: 0 – Do Minimum, 1 – Routine Maintenance, 2 – Periodic Maintenance, 3 – Rehabilitation

Table B-3: Selected M&R Program under Rs.100 Million Budget Level using Genetic Algorithm

Road Link Name	Existing IRI (m/km)	Pothole (Nos)	Selected Strategy	Post Condition IRI (m/km)	Project Cost (LKR)
C008/Sec0001	2.5	4	0	2.5	67,470
C005/Sec0001	2.7	3	0	2.7	67,470
D004/Sec0001	2.9	0	0	2.9	67,470
C004/Sec0001	3.1	1	0	3.1	67,470
C008/Sec0002	3.4	5	0	3.4	67,470
C005/Sec0002	3.6	9	0	3.6	67,470
D004/Sec0002	3.7	0	0	3.7	67,470
C004/Sec0002	4.4	0	1	3.9	179,671
D005/Sec0002	5.0	4	2	2.8	4,198,091
C002/Sec0001	5.2	0	2	2.8	4,234,167
D002/Sec0001	5.3	6	1	4.2	294,830
C003/Sec0002	5.4	0	2	2.8	4,979,101
C003/Sec0001	5.7	0	2	2.8	5,073,774
C301/Sec0004	6.0	10	2	3.0	4,463,435
D002/Sec0003	6.1	5	2	3.1	4,504,523
D005/Sec0001	6.1	4	1	4.5	544,523
C301/Sec0001	6.3	8	2	3.1	4,597,044
C300/Sec0001	6.4	14	2	3.2	4,648,841
C301/Sec0002	6.7	6	2	3.2	4,828,322
C300/Sec0002	6.9	18	2	3.3	4,969,270
C300/Sec0003	7.8	14	2	3.3	5,810,265
C300/Sec0004	8.2	12	2	3.3	6,260,692
D002/Sec0004	8.7	26	2	2.8	7,277,036
C301/Sec0003	9.2	35	2	3.0	7,334,588
C002/Sec0002	9.3	13	2	2.9	7,425,073
D002/Sec0002	10.0	19	2	3.1	7,937,098
D005/Sec0003	11.0	29	2	2.9	8,342,586

Selected Strategy: 0 – Do Minimum, 1 – Routine Maintenance, 2 – Periodic Maintenance, 3 – Rehabilitation

Table B-4: The Hypothetical Road Network for Case Study

Road Link Name	**Pavement Type**	**Existing IRI (m/km)**	**Pothole (Nos)**	**ADT (veh/day)**
A001	Asphalt	2.4	0	500
C001	Concrete	3.0	0	250
A002	Asphalt	3.1	0	600
A003	Asphalt	3.2	0	900
A004	Asphalt	4.4	1	670
C002	Concrete	4.6	0	1,200
G001	Gravel	5.8	3	1,400
A005	Asphalt	6.0	13	2,600
A006	Asphalt	5.0	4	4,000
G002	Gravel	5.2	5	1,500
A007	Asphalt	6.5	14	500
G003	Gravel	8.0	18	170
C003	Concrete	6.0	4	2,500
C004	Concrete	9.0	12	450
A008	Asphalt	6.4	18	2,400
G004	Gravel	13.0	40	560
A009	Asphalt	8.2	35	325
C005	Concrete	11.0	20	3,400
A010	Asphalt	9.0	40	670
C006	Concrete	10.5	19	300
A011	Asphalt	12.0	51	400
A012	Asphalt	5.6	26	1500
C007	Concrete	7.5	35	1200
C008	Concrete	6.3	29	580
G005	Gravel	8.0	39	780
A001	Asphalt	2.4	0	500
C001	Concrete	3.0	0	250

Table B-5: Summary of Engineer's Response for the Case Study

Engineer Response ID.	50 Million Budget		75 Million Budget		100 Million Budget	
	Average Network IRI (m/km)	Total Cost (Rs.)	Average Network IRI (m/km)	Total Cost (Rs.)	Average Network IRI (m/km)	Total Cost (Rs.)
1	5.43	48,479,033	4.39	74,352,633	3.68	94,697,933
2	5.31	49,697,033	4.44	74,743,133	3.66	99,267,233
3	4.83	48,000,000	3.99	75,000,000	3.81	100,000,000
4	4.76	49,783,288	4.00	74,349,877	3.78	87,073,588
5	5.33	49,778,433	4.24	73,766,633	3.66	99,267,233
6	4.90	49,816,433	4.08	73,135,633	3.66	97,352,233
7	4.63	49,895,000	4.11	74,737,500	3.66	99,270,000
8	5.47	47,523,566	4.29	71,731,990	3.92	85,997,290
9	5.91	41,909,786	-	-	3.66	97,352,233
10	5.34	49,344,490	4.50	72,005,552	3.90	99,218,582
11	4.76	49,783,288	4.00	74,349,877	3.78	87,073,588
12	4.99	49,526,528	4.06	74,489,741	3.66	97,195,477
13	4.80	49,012,608	4.03	74,224,118	3.71	95,618,866
14	5.17	48,510,274	4.21	74,968,590	3.72	91,286,496
15	5.50	45,304,761	4.29	71,731,990	3.92	85,997,290
16	5.47	47,428,314	4.29	71,880,696	3.78	87,867,890
17	5.20	49,586,033	4.77	75,150,133	4.29	82,741,433
18	4.83	49,482,555	4.09	69,587,279	3.78	89,222,790

Engineer Response ID.	50 Million Budget		75 Million Budget		100 Million Budget	
	Average Network IRI (m/km)	Total Cost (Rs.)	Average Network IRI (m/km)	Total Cost (Rs.)	Average Network IRI (m/km)	Total Cost (Rs.)
19	5.44	44,597,233	4.78	74,278,233	4.34	94,964,933
20	5.29	47,376,733	4.36	72,548,633	3.87	93,644,333
21	4.80	44,730,850	4.00	69,895,350	3.78	97,352,233
22	4.85	48,744,500	4.20	71,148,796	3.66	97,025,356
23	5.18	49,722,933	4.56	74,894,833	3.66	99,267,233
24	5.17	48,042,037	4.45	73,506,990	3.66	97,352,233
25	5.20	49,771,033	4.12	74,263,833	3.66	99,267,233
26	5.33	49,778,433	4.26	74,875,733	3.77	99,731,733
27	6.16	45,022,452	5.55	67,524,742	4.79	90,175,136
28	5.94	45,040,526	5.61	67,558,042	4.63	94,108,608
29	6.12	45,102,673	5.34	67,982,020	4.32	97,370,023
30	6.13	45,340,212	5.60	68,015,678	4.38	97,949,783
31	6.13	45,601,360	5.05	68,079,307	4.53	98,028,216
32	6.10	45,767,637	5.56	68,556,879	4.38	98,182,595
33	6.06	46,040,038	5.28	74,369,858	4.41	99,233,609
34	5.95	46,052,596	5.14	74,823,644	4.18	99,738,133
35	6.07	46,663,646	5.09	74,882,865	4.26	99,738,133
36	6.01	46,776,219	4.89	74,987,662	4.26	99,801,033
37	6.11	46,845,570	4.96	69,065,074	4.59	99,823,833
38	5.80	47,356,050	4.93	74,662,310	4.25	99,917,525

Engineer Response ID.	50 Million Budget		75 Million Budget		100 Million Budget	
	Average Network IRI (m/km)	**Total Cost (Rs.)**	**Average Network IRI (m/km)**	**Total Cost (Rs.)**	**Average Network IRI (m/km)**	**Total Cost (Rs.)**
39	5.94	48,214,410	4.78	74,745,202	4.14	99,926,821
40	5.51	49,855,340	4.58	74,958,882	4.58	70,921,124
41	5.36	49,947,760	4.76	74,970,322	4.57	74,397,465
42	5.63	49,989,872	5.50	68,008,509	4.49	73,528,922
43	5.40	49,998,515	5.54	68,756,030	3.96	93,967,922
Mean	5.45		4.64		4.03	
Standard Deviation	0.47		0.53		0.35	
Coefficient of Variation (CV)	9%		11%		9%	

Appendix-C: Road Network Details for Multi-Objective Optimization Approach

Table C-1: Summarization of Literature Analysis to Establish the Intervention Levels used in the Analysis Scheme

Pavement Type	Maintenance Strategy	Work Standards of RDA for Low Volume Roads [29]	National Road Master Plan 2018-2027 [26]	Intervention Level in Worldwide [40], [41] [121] – [133]	Selected Intervention Level
Flexible	Routine	Crack seal; > 10% Pothole; > 10 Nos/km Edge Breaking > 50 m^2/km	IRI < 3.5 m/km	Spain; IRI < 6 m/km Canada; IRI > 3.3 m/km Ireland; IRI > 5 m/km Kazakhstan; IRI > 3.4 m/km Lithuania; IRI > 4.5 m/km Norway; IRI > 5 m/km New Zealand; IRI > 5.7 m/km Russia; IRI > 4.2 m/km Sweden; IRI > 5.8 m/km Portugal; IRI > 3.5 m/km	IRI > 4 m/km
	Periodic	IRI > 5m/km Damage Area > 20% Every 5 year	IRI 3.5 – 8 m/km	Cyprus; IRI > 6 m/km Spain; 6 – 8 m/km Mali, Chile, Costa Rica; IRI > 5 m/km	IRI > 4 m/km
	Rehabilitation/ Reconstruction	-	IRI > 8m/km	Spain; IRI > 8 m/km Australia; IRI > 6.1 m/km Czech Republic; IRI > 6.3 m/km Poland; IRI > 6.6 m/km Slovakia; IRI > 8 m/km Mali, Chile, Costa Rica; IRI > 8.5 m/km	IRI > 7 m/km

Pavement Type	Maintenance Strategy	Work Standards of RDA for Low Volume Roads [29]	National Road Master Plan 2018-2027 [26]	Intervention Level in Worldwide [40], [41] [121] – [133]	Selected Intervention Level
Concrete	Routine	Damage Area > 20%	Damage Area > 10%	Kazakhstan; IRI > 3.4 m/km Norway; IRI > 5 m/km Russia; IRI > 4.2 m/km	IRI > 5m/km
	Periodic	Crack Area > 10%	IRI > 5m/km Damage Area > 20%	Mali, Chile, Costa Rica; IRI > 5 m/km	IRI > 5m/km
	Rehabilitation/ Reconstruction	-	Damage Area > 50%	Czech Republic; IRI > 6.3 m/km Poland; IRI > 6.6 m/km Mali, Chile, Costa Rica; IRI > 8.5 m/km	IRI > 10 m/km

Table C-2: Road Inventory Data and Priority Index Data of Case Study Network-Negombo

Link No.	Road Link Name	Pavement Type	Road width	Land Use		Connectivity		Traffic volume	Alternative routes	Road Roughness (IRI)	Priority Value (Fi)				Weighted PI	Is it a Priority Road?
				Type	Extend	Start	End				Land Use	Connectivity	Traffic Volume	Community Importance		
1	No Name - 1	AC	3.1	Residential	M	PS	DE	L	No	8.5	5	5	5	0	25.0	-
2	Mangala Rd	AC	4.0	Residential	M	PS	Minor	L	Yes	4.2	5	7	5	5	48.5	-
3	VC DeSilva Mw	CC	3.0	Residential	M	PS	DE	L	No	4.5	5	5	5	0	25.0	-
4	Vijaya Rd	AC	5.2	Residential	M	PS	Minor	L	Yes	8.0	5	7	5	5	48.5	-
5	Rathna Mw	AC	3.5	Residential	M	PS	Minor	L	Yes	3.9	5	7	5	5	48.5	-
6	Gamini Rd	AC	3.5	Residential	M	PS	DE	L	No	8.0	5	5	5	0	25.0	-
7	Vincent Perera Mw	CC	2.8	Residential	M	Minor	DE	VL	No	5.0	5	2	3	0	15.8	-
8	Ranaviru Anil Perera Mw	CC	3.0	Residential	M	PS	DE	L	No	4.8	5	5	5	0	25.0	-
9	Suhada Mw	CC	2.9	Residential	M	PS	DE	L	No	4.5	5	5	5	0	25.0	-
10	No Name - 2	CC	2.7	Residential	M	PS	DE	L	No	4.6	5	5	5	0	25.0	-
11	St.Anne's Rd	AC	5.8	Residential	M	CD	CD	M	Yes	3.0	5	14	7	5	64.8	Priority Road
12	E John Silva Mw	CC	3.3	Residential	M	PS	Minor	L	Yes	11.0	5	7	5	5	48.5	-
13	St.Jude Vidyala Mw	CC	3.9	Residential	M	PS	Minor	L	Yes	4.9	5	7	5	5	48.5	-
14	Parakrama Rd	AC	4.4	Residential	M	CD	Minor	M	Yes	3.4	5	9	7	5	56.0	Priority Road
15	Thalduwa Rd	AC	6.1	Residential	H	AB	CD	H	Yes	3.7	20	17	10	5	94.8	Priority Road
				Commercial	H											

Link No.	Road Link Name	Pavement Type	Road width	Land Use		Connectivity		Traffic volume	Alternative routes	Road Roughness (IRI)	Priority Value (Fi)				Weighted PI	Is it a Priority Road?
				Type	Extend	Start	End				Land Use	Connectivity	Traffic Volume	Community Importance		
16	No Name - 3	AC	4.0	Residential	H	CD	CD	M	Yes	10.0	10	14	7	5	71.0	Priority Road
17	No Name - 4	AC	4.3	Residential	H	PS	PS	L	Yes	2.8	10	10	5	5	60.0	Priority Road
18	De Silva Mw	AC	3.9	Residential	H	CD	Minor	M	Yes	11.4	10	9	7	5	62.3	Priority Road
19	Rukmani Devi Mw	AC	5.8	Residential	H	AB	CD	H	Yes	7.5	10	17	10	5	82.3	Priority Road
20	Katuwapitiya Rd	AC	5.8	Residential	H	AB	CD	H	Yes	10.5	10	17	10	5	82.3	Priority Road
21	No Name - 5	AC	4.2	Residential	H	CD	DE	M	No	2.6	20	7	7	0	51.3	Priority Road
				Commercial	H											
22	Main St	AC	7.3	Residential	H	AB	AB	H	Yes	8.5	10	20	10	5	87.5	Priority Road
23	Chilaw Rd	AC	6.8	Residential	H	AB	CD	H	Yes	7.9	20	17	10	5	94.8	Priority Road
				Commercial	H											
24	Adnivas Rd	AC	6.5	Residential	H	CD	Minor	M	Yes	10.7	10	9	7	5	62.3	Priority Road
25	Jumma Masjid Mw	AC	6.5	Residential	H	AB	CD	H	Yes	2.9	10	17	10	5	82.3	Priority Road
26	St.Anthony's Rd	CC	5.5	Residential	M	PS	Minor	L	Yes	4.9	5	7	5	5	48.5	-
27	St.Lazarus Rd	AC	4.4	Residential	M	CD	CD	M	Yes	9.4	5	14	7	5	64.8	Priority Road
28	Prison Rd	AC	5.0	Residential	M	CD	Minor	M	Yes	7.3	10	9	7	5	62.3	Priority Road
				Commercial	M											
29	No Name - 6	CC	3.5	Residential	M	PS	Minor	L	Yes	4.6	5	7	5	5	48.5	-
30	No Name - 7	CC	3.6	Residential	M	PS	Minor	L	Yes	4.8	5	7	5	5	48.5	-

Link No.	Road Link Name	Pavement Type	Road width	Land Use		Connectivity		Traffic volume	Alternative routes	Road Roughness (IRI)	Priority Value (Fi)				Weighted PI	Is it a Priority Road?
				Type	Extend	Start	End				Land Use	Connectivity	Traffic Volume	Community Importance		
31	No Name - 8	AC	4.9	Residential	M	CD	Minor	M	Yes	9.0	5	9	7	5	56.0	Priority Road
32	Station Rd	AC	3.0	Residential	M	CD	CD	M	Yes	7.6	5	14	7	5	64.8	Priority Road
33	St. Jude Rd	CC	3.2	Residential	M	PS	Minor	L	Yes	9.5	5	7	5	5	48.5	-
34	Mark Sebastian Mw	AC	3.2	Residential	M	PS	Minor	L	Yes	6.3	5	7	5	5	48.5	-
35	Kurunduwatta Rd	CC	3.5	Residential	M	PS	Minor	L	Yes	5.3	5	7	5	5	48.5	-
36	No Name - 9	CC	3.0	Residential	M	Minor	DE	VL	No	5.2	5	2	3	0	15.8	-
37	Convent Rd	CC	3.5	Residential	M	PS	Minor	L	Yes	5.4	5	7	5	5	48.5	-
38	Baseline Rd	AC	5.0	Residential	M	CD	Minor	M	Yes	11.2	5	9	7	5	56.0	Priority Road
39	Subhasadka Mw	AC	3.7	Residential	M	PS	Minor	L	Yes	4.2	5	7	5	5	48.5	-
40	Janapada Mw	AC	3.6	Residential	M	CD	CD	M	Yes	8.2	5	14	7	5	64.8	Priority Road
41	No Name - 10	AC	4.5	Residential	M	CD	PS	M	Yes	4.1	10	12	7	5	67.5	Priority Road
				Commercial	M											
42	Kristhuraja Mw	CC	3.0	Residential	M	PS	DE	L	No	7.2	5	5	5	0	25.0	-
43	No Name - 11	GR	3.1	Residential	M	Minor	DE	VL	No	10.5	5	2	3	0	15.8	-
44	KC De Silva Mw	AC	3.0	Residential	M	Minor	PS	VL	Yes	5.4	5	7	3	5	44.5	-
45	No Name - 12	CC	3.4	Residential	M	PS	Minor	L	Yes	12.5	5	7	5	5	48.5	-
46	No Name - 13	GR	3.9	Residential	M	PS	Minor	L	Yes	6.8	5	7	5	5	48.5	-
47	Fatima Rd	GR	2.8	Residential	M	PS	Minor	L	Yes	3.6	5	7	5	5	48.5	-

Link No.	Road Link Name	Pavement Type	Road width	Land Use		Connectivity		Traffic volume	Alternative routes	Road Roughness (IRI)	Priority Value (Fi)				Weighted PI	Is it a Priority Road?
				Type	Extend	Start	End				Land Use	Connectivity	Traffic Volume	Community Importance		
48	No Name - 14	AC	3.6	Residential	M	PS	Minor	L	Yes	4.7	5	7	5	5	48.5	-
49	Poruthota Rd	AC	6.0	Residential	M	CD	PS	M	Yes	8.5	5	12	7	5	61.3	Priority Road
50	Church Rd	AC	3.7	Residential	M	PS	Minor	L	Yes	8.2	5	7	5	5	48.5	-
51	Archbishop Nicholas Marcus Fernando Mw	AC	7.2	Residential	H	AB	CD	H	Yes	8.3	10	17	10	5	82.3	Priority Road
52	Sri Wickrama Rajasinghe Rd	AC	4.6	Residential	M	CD	PS	M	Yes	7.2	5	12	7	5	61.3	Priority Road
53	Temple Rd	AC	6.5	Residential Commercial	H H	AB	CD	H	Yes	9.3	20	17	10	5	94.8	Priority Road
54	Custom House Rd	AC	6.5	Commercial	H	CD	Minor	M	Yes	3.6	10	9	7	5	62.3	Priority Road
55	No Name - 15	AC	2.6	Residential	H	CD	PS	M	Yes	9.2	10	12	7	5	67.5	Priority Road
56	Christopher Rd	CC	3.5	Residential	H	CD	CD	M	Yes	5.1	10	14	7	5	71.0	Priority Road
57	No Name - 16	CC	3.0	Residential	H	PS	Minor	L	Yes	10.4	10	7	5	5	54.8	Priority Road
58	Malwatta Rd	AC	3.0	Residential	H	PS	Minor	L	Yes	8.3	10	7	5	5	54.8	Priority Road
59	4th Lane	AC	6.0	Residential	H	Minor	Minor	L	Yes	4.6	10	4	5	5	49.5	-
60	No Name - 17	AC	6.0	Residential	H	Minor	Minor	L	Yes	4.5	10	4	5	5	49.5	-
61	No Name - 18	AC	7.0	Residential	H	Minor	Minor	L	Yes	7.5	10	4	5	5	49.5	-
62	Adnives Rd	AC	6.0	Residential	H	CD	PS	M	Yes	3.5	10	12	7	5	67.5	Priority Road
63	Perera Pl	CC	7.5	Residential	M	Minor	Minor	L	Yes	4.6	5	4	5	5	43.3	-

Link No.	Road Link Name	Pavement Type	Road width	Land Use		Connectivity		Traffic volume	Alternative routes	Road Roughness (IRI)	Priority Value (Fi)				Weighted PI	Is it a Priority Road?
				Type	Extend	Start	End				Land Use	Connectivity	Traffic Volume	Community Importance		
64	No Name - 19	CC	4.0	Residential	M	Minor	Minor	L	Yes	5.3	5	4	5	5	43.3	-
65	St. Jude Mw	CC	3.5	Residential	M	Minor	Minor	VL	Yes	6.2	5	4	3	5	39.3	-
66	St. Anthony's Rd	AC	3.6	Residential	M	Minor	Minor	VL	Yes	4.3	5	4	3	5	39.3	-
67	St. Joseph Mw	CC	3.6	Residential	M	Minor	Minor	VL	Yes	4.6	5	4	3	5	39.3	-
68	St. Sylvester Rd	AC	3.5	Residential	M	Minor	Minor	L	Yes	11.5	5	4	5	5	43.3	-
69	Thakkiya Rd	AC	3.5	Residential	M	Minor	Minor	L	Yes	8.8	5	4	5	5	43.3	-
70	Ground Rd	AC	3.3	Residential	M	Minor	Minor	L	Yes	6.5	5	4	5	5	43.3	-
71	Silversand Rd	AC	4.2	Residential	M	PS	Minor	L	Yes	4.6	5	7	5	5	48.5	-
72	Holy Trinity Church Rd	AC	3.8	Residential	M	Minor	Minor	VL	Yes	9.5	5	4	3	5	39.3	-
73	Mosque Lane	CC	4.5	Residential	M	Minor	Minor	L	Yes	5.4	5	4	5	5	43.3	-
74	No Name - 20	CC	3.6	Residential	M	Minor	DE	VL	No	10.8	5	2	3	0	15.8	-
75	No Name - 21	CC	3.3	Residential	L	Minor	DE	VL	No	4.7	2	2	3	0	12.0	-
76	No Name - 22	CC	3.0	Residential	L	Minor	DE	VL	No	5.4	2	2	3	0	12.0	-
77	No Name - 23	CC	2.0	Residential	L	Minor	Minor	VL	Yes	9.5	2	4	3	5	35.5	-
78	No Name - 24	AC	2.5	Residential	L	Minor	Minor	VL	Yes	5.7	2	4	3	5	35.5	-
79	No Name - 25	CC	3.6	Residential	L	PS	Minor	L	Yes	6.2	2	7	5	5	44.8	-
80	St. Martin's Rd	AC	3.3	Residential	L	PS	Minor	L	Yes	12.0	2	7	5	5	44.8	-
81	No Name - 26	CC	2.5	Residential	L	Minor	DE	VL	No	5.6	2	2	3	0	12.0	-

Link No.	Road Link Name	Pavement Type	Road width	Land Use		Connectivity		Traffic volume	Alternative routes	Road Roughness (IRI)	Priority Value (Fi)				Weighted PI	Is it a Priority Road?
				Type	Extend	Start	End				Land Use	Connectivity	Traffic Volume	Community Importance		
82	No Name - 77	AC	3.2	Residential	L	Minor	DE	VL	No	4.8	2	2	3	0	12.0	-
83	No Name - 78	CC	3.5	Residential	L	Minor	DE	VL	No	5.2	2	2	3	0	12.0	-
84	No Name - 79	CC	3.8	Residential	L	Minor	DE	VL	No	5.0	2	2	3	0	12.0	-
85	No Name - 80	CC	3.3	Residential	L	Minor	DE	VL	No	4.8	2	2	3	0	12.0	-
86	Pitipana Street	AC	3.4	Residential	L	Minor	DE	VL	No	7.4	2	2	3	0	12.0	-
87	No Name - 81	CC	3.0	Residential	L	Minor	DE	L	No	6.0	2	2	5	0	16.0	-
88	Duwa Rd	AC	3.8	Residential	L	PS	Minor	L	Yes	4.7	4	7	5	5	47.3	-
				Industrial	L											
89	Newton Rd	CC	4.0	Residential	L	Minor	PS	L	Yes	4.8	4	7	5	5	47.3	-
				Commercial	L											
90	No Name - 82	CC	3.5	Residential	L	PS	DE	L	No	5.3	2	5	5	0	21.3	-
91	St. Martin's Rd	AC	3.8	Residential	L	PS	Minor	L	Yes	9.3	2	7	5	5	44.8	-
92	No Name - 83	CC	3.0	Residential	L	PS	DE	L	No	5.6	2	5	5	0	21.3	-
93	No Name - 84	CC	3.5	Residential	L	PS	Minor	L	Yes	10.5	4	7	5	5	47.3	-
				Industrial	L											
94	St. Sebestian Rd	AC	3.0	Residential	M	Minor	Minor	L	Yes	5.2	5	4	5	5	43.3	-

Pavement Type: AC – Asphalt Concrete, CC – Cement Concrete, GR – Gravel

Land Use: H – High Extend, M – Medium Extend, L – Low Extend

Connectivity: AB – Class A & B roads, CD – Class C & D roads, PS – Pradeshiya Sabha roads, Minor – Minor roads, DE – Dead End

Traffic Volume: H – High, M – Moderate, L – Low, VL – Very Low

Table C-3: Selected Maintenance Strategies for Each Road Segment in Three Different Budgetary Levels

Link No.	Road Link Name	Pavement Type	Existing Road Roughness (IRI)	Priority Road/Non-Priority Road	40% of the Total Budget Requirement		60% of the Total Budget Requirement		80% of the Total Budget Requirement	
					Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)
1	No Name - 1	AC	8.5	-	1	6.8	1	6.8	2	3.5
2	Mangala Rd	AC	4.2	-	1	4.2	1	4.2	1	4.2
3	VC DeSilva Mw	CC	4.5	-	1	4.5	1	4.5	1	4.5
4	Vijaya Rd	AC	8.0	-	1	7.0	1	7.0	3	2.3
5	Rathna Mw	AC	3.9	-	0	3.9	0	3.9	0	3.9
6	Gamini Rd	AC	8.0	-	1	7.5	2	3.5	2	3.5
7	Vincent Perera Mw	CC	5.0	-	1	4.5	1	4.5	1	4.5
8	Ranaviru Anil Perera Mw	CC	4.8	-	0	4.8	0	4.8	0	4.8
9	Suhada Mw	CC	4.5	-	1	4.5	0	4.5	0	4.5
10	No-Name-2	CC	4.6	-	1	4.6	0	4.6	0	4.6
11	St.Anne's Rd	AC	3.0	Priority Road	0	3.0	0	3.0	0	3.0
12	E John Silva Mw	CC	11.0	-	2	4.5	2	4.5	2	4.5

Link No.	Road Link Name	Pavement Type	Existing Road Roughness (IRI)	Priority Road/Non-Priority Road?	40% of the Total Budget Requirement		60% of the Total Budget Requirement		80% of the Total Budget Requirement	
					Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)
13	St.Jude Vidyala Mw	CC	4.9	-	0	4.9	1	4.9	0	4.9
14	Parakrama Rd	AC	3.4	Priority Road	0	3.4	0	3.4	0	3.4
15	Thalduwa Rd	AC	3.7	Priority Road	0	3.7	1	3.7	1	3.7
16	No Name - 3	AC	10.0	Priority Road	2	3.4	3	2.3	3	2.3
17	No Name - 4	AC	2.8	Priority Road	0	2.8	0	2.8	0	2.8
18	De Silva Mw	AC	11.4	Priority Road	2	3.3	2	3.3	3	2.3
19	Rukmani Devi Mw	AC	7.5	Priority Road	1	6.0	3	2.3	3	2.3
20	Katuwapitiya Rd	AC	10.5	Priority Road	2	3.3	3	2.3	3	2.3
21	No Name - 5	AC	2.6	Priority Road	0	2.6	0	2.6	1	2.6
22	Main St	AC	8.5	Priority Road	1	7.5	3	2.3	3	2.3
23	Chilaw Rd	AC	7.9	Priority Road	1	6.3	3	2.3	3	2.3
24	Adnivas Rd	AC	10.7	Priority Road	1	9.2	3	2.3	3	2.3
25	Jumma Masjid Mw	AC	2.9	Priority Road	0	2.9	0	2.9	0	2.9
26	St.Anthony's Rd	CC	4.9	-	0	4.9	0	4.9	0	4.9
27	St.Lazarus Rd	AC	9.4	Priority Road	2	3.2	3	2.3	3	2.3
28	Prison Rd	AC	7.3	Priority Road	1	6.5	3	2.3	3	2.3
29	No Name - 6	CC	4.6	-	1	4.6	0	4.6	0	4.6
30	No Name - 7	CC	4.8	-	0	4.8	0	4.8	0	4.8

Link No.	Road Link Name	Pavement Type	Existing Road Roughness (IRI)	Priority Road/Non-Priority Road	40% of the Total Budget Requirement		60% of the Total Budget Requirement		80% of the Total Budget Requirement	
					Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)
31	No Name - 8	AC	9.0	Priority Road	1	7.5	3	2.3	3	2.3
32	Station Rd	AC	7.6	Priority Road	2	3.4	2	3.4	2	3.4
33	St. Jude Rd	CC	9.5	-	2	4.5	2	4.5	2	4.5
34	Mark Sebestian Mw	AC	6.3	-	1	5.5	1	5.5	2	3.5
35	Kurunduwatta Rd	CC	5.3	-	2	4.5	2	4.5	2	4.5
36	No Name - 9	CC	5.2	-	2	4.5	2	4.5	1	4.9
37	Convent Rd	CC	5.4	-	2	4.5	2	4.5	2	4.5
38	Baseline Rd	AC	11.2	Priority Road	3	2.3	3	2.3	3	2.3
39	Subhasadka Mw	AC	4.2	-	1	4.2	1	4.2	2	3.3
40	Janapada Mw	AC	8.2	Priority Road	2	3.3	2	3.3	3	2.3
41	No Name - 10	AC	4.1	Priority Road	1	4.1	1	4.1	2	3.2
42	Kristhuraja Mw	CC	7.2	-	0	4.5	1	4.5	0	4.5
43	No Name - 11	GR	10.5	-	1	9.5	1	9.5	1	9.5
44	KC De Silva Mw	AC	5.4	-	2	3.6	2	3.6	2	3.6
45	No-Name-12	CC	12.5	-	2	4.5	2	4.5	2	4.5
46	No-Name-13	GR	6.8	-	2	5.0	2	5.0	2	5.0
47	Fatima Rd	GR	3.6	-	1	6.1	1	6.1	1	6.1
48	No Name - 14	AC	4.7	-	0	3.6	0	3.6	0	3.6

Link No.	Road Link Name	Pavement Type	Existing Road Roughness (IRI)	Priority Road/Non-Priority Road	40% of the Total Budget Requirement		60% of the Total Budget Requirement		80% of the Total Budget Requirement	
					Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)
49	Poruthota Rd	AC	8.5	Priority Road	1	4.7	1	4.7	2	3.4
50	Church Rd	AC	8.2	-	1	7.8	1	7.8	2	3.5
51	Archbishop Nicholas Marcus Fernando Mw	AC	8.3	Priority Road	1	7.2	3	2.3	3	2.3
52	Sri Wickrama Rajasinghe Rd	AC	7.2	Priority Road	2	3.4	3	2.3	3	2.3
53	Temple Rd	AC	9.3	Priority Road	3	2.3	3	2.3	3	2.3
54	Custom House Rd	AC	3.6	Priority Road	1	3.6	0	3.6	1	3.6
55	No Name - 15	AC	9.2	Priority Road	2	3.4	2	3.4	2	3.4
56	Christopher Rd	CC	5.1	Priority Road	2	4.5	2	4.5	2	4.5
57	No Name - 16	CC	10.4	Priority Road	2	4.5	3	3.7	3	3.7
58	Malwatta Rd	AC	8.3	Priority Road	2	3.3	2	3.3	3	2.3
59	4th Lane	AC	4.6	-	1	4.6	1	4.6	1	4.6
60	No Name - 17	AC	4.5	-	1	4.5	1	4.5	1	4.5
61	No Name - 18	AC	7.5	-	1	6.3	1	6.3	2	3.0
62	Adnives Rd	AC	3.5	Priority Road	0	3.5	1	3.5	1	3.5
63	Perera Pl	CC	4.6	-	0	4.6	0	4.6	0	4.6
64	No Name - 19	CC	5.3	-	2	4.5	2	4.5	2	4.5
65	St. Jude Mw	CC	6.2	-	2	4.6	2	4.6	2	4.6

Link No.	Road Link Name	Pavement Type	Existing Road Roughness (IRI)	Priority Road/Non-Priority Road	40% of the Total Budget Requirement		60% of the Total Budget Requirement		80% of the Total Budget Requirement	
					Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)
66	St. Anthony's Rd	AC	4.3	-	1	4.3	1	4.3	1	4.3
67	St. Joseph Mw	CC	4.6	-	0	4.6	0	4.6	0	4.6
68	St. Sylvester Rd	AC	11.5	-	1	8.5	2	3.7	3	2.3
69	Thakkiya Rd	AC	8.8	-	1	7.6	1	7.6	2	3.4
70	Ground Rd	AC	6.5	-	1	5.7	2	3.3	2	3.3
71	Silversand Rd	AC	4.6	-	1	4.6	1	4.6	2	3.4
72	Holy Trinity Church Rd	AC	9.5	-	1	7.5	2	3.4	2	3.4
73	Mosque Lane	CC	5.4	-	2	4.5	2	4.5	2	4.5
74	No Name - 20	CC	10.8	-	2	4.5	2	4.5	2	4.5
75	No Name - 21	CC	4.7	-	0	4.7	1	4.7	0	4.7
76	No Name - 22	CC	5.4	-	2	4.5	2	4.5	2	4.5
77	No Name - 23	CC	9.5	-	2	4.5	2	4.5	2	4.5
78	No Name - 24	AC	5.7	-	2	3.5	1	5.7	2	3.5
79	No Name - 25	CC	6.2	-	2	4.5	2	4.5	2	4.5
80	St. Martin's Rd	AC	12.0	-	2	3.4	2	3.4	3	2.3
81	No Name - 26	CC	5.6	-	2	4.5	2	4.5	2	4.5
82	No Name - 77	AC	4.8	-	1	4.8	1	4.8	2	3.4
83	No Name - 78	CC	5.2	-	2	4.5	2	4.5	2	4.5
84	No Name - 79	CC	5.0	-	1	5.0	1	5.0	1	5.0

Link No.	Road Link Name	Pavement Type	Existing Road Roughness (IRI)	Priority Road/Non-Priority Road	40% of the Total Budget Requirement		60% of the Total Budget Requirement		80% of the Total Budget Requirement	
					Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)	Selected Maintenance Strategy (r)	Post Condition IRI (m/km)
85	No Name - 80	CC	4.8	-	0	4.8	1	4.8	1	4.8
86	Pitipana Street	AC	7.4	-	1	6.9	2	3.5	2	3.5
87	No Name - 81	CC	6.0	-	2	4.6	2	4.6	2	4.6
88	Duwa Rd	AC	4.7	-	1	4.7	1	4.7	1	4.7
89	Newton Rd	CC	4.8	-	0	4.8	0	4.8	0	4.8
90	No Name - 82	CC	5.3	-	2	4.5	2	4.5	2	4.5
91	St. Martin's Rd	AC	9.3	-	1	7.8	1	7.8	2	3.4
92	No Name - 83	CC	5.6	-	2	4.5	2	4.5	2	4.5
93	No Name - 84	CC	10.5	-	2	4.5	2	4.5	3	3.7
94	St. Sebestian Rd	AC	5.2	-	1	4.9	1	4.9	1	4.9

Table C-4: Road Inventories Collected for the Case Study Incoperating Safety Performance

Road ID.	Name of the Road Segment	Pavement Type	Road Width (m)	Length (km)	Existing IRI (m/km)	Existing CSI value
1	C210	AC	3.0	2.3	2.4	525
2	Demodera - Spring Valley - Badulla	AC	3.4	1.7	2.7	633
3	Wakwella - Dodangoda Road	CC	3.5	1.8	3	765
4	C230	AC	3.4	2.3	3.1	869
5	C216	AC	3.5	2.9	3.2	923
6	Old Higurana Road	AC	3.6	2.4	4.4	639
7	Poonagala Road	CC	3.0	1.8	4.6	566
8	Eravur Punnakudah Road	GR	3.0	2	4.8	865
9	Puttur - Meesalai Rd	AC	3.5	2	4.8	426
10	C240	AC	3.6	1.4	4.8	367
11	C002	AC	4.0	2.3	5	546
12	Dombagahalwewa - Dematabedda - Mariarawa Rd	CC	3.7	1.6	5.2	285
13	D001	AC	4.0	2.3	5.3	427
14	C220	GR	3.0	1.6	5.5	501
15	C250	AC	3.0	1.7	5.5	356
16	C001	AC	3.0	1.6	6	345
17	D047	CC	3.0	2.6	6	458
18	Vantharumoolai Kaluwankeny Road	CC	3.4	1.6	6.1	174
19	C300	AC	4.0	1.6	6.4	156
20	Vallai - Telippalai - Araly	GR	4.0	2.1	7.6	182
21	Mavilaru Junction to Seruvila Main road	AC	3.9	1.1	8.2	203
22	D510	CC	3.7	1.5	8.5	380
23	C100	AC	3.7	2.4	9	327
24	C003	AC	4.0	1.8	9.3	423
25	C200	CC	3.0	2	10.5	305

Pavement Type: AC – Asphalt Concrete, CC – Cement Concrete, GR – Gravel

Appendix-D: The List of Publications from the Dissertation

Table D-1: List of Publications from the Dissertation

No.	Title of the Publication	Name of the Journal/Conference	Type of Index	Rank Indicator
01	Applicability of Smartphone-based Roughness Data for Rural Road Pavement Condition Evaluation	International Journal of Pavement Engineering	Scopus Indexed	Q1
02	Development of Pavement Roughness Prediction Model for National Highways in Sri Lanka	Journal of the Institute of Engineers Sri Lanka	ESCI	-
03	A Framework for Network Level Pavement Maintenance Planning for Low Volume Roads	9th International Conference on Maintenance and Rehabilitation of Pavements—MAIREPAV9	Scopus Indexed	-
04	A Framework to Incorporate Safety Performance for Low Volume Roads in Pavement Management Systems	6th International Multidisciplinary Moratuwa Engineering Research Conference (MERCon)	Scopus Indexed	-
05	Pavement Maintenance Management System for Low Volume Roads in Sri Lanka	5th International Multidisciplinary Moratuwa Engineering Research Conference (MERCon)	Scopus Indexed	-
06	Applicability of Smartphone-based Roughness Data for Rural Road Network Level Pavement Condition Evaluation	99th Annual Meeting of Transportation Research Board (Presentation)	-	-
07	Development of Pavement Condition Prediction Model for National Highways	Transport Research Forum 2019 (Abstract)	-	-
Co-Authored				
No.	**Title of the Publication**	**Name of the Journal/Conference**	**Type of Index**	**Rank Indicator**
08	Incorporating Road Safety into Rural Road Network Pavement Management	International Journal of Pavement Engineering	Scopus Indexed	Q1
09	Identification of the Impact on Road Roughness on Speed Patterns for Different Roadway Segments	6th International Multidisciplinary Moratuwa Engineering Research Conference (MERCon)	Scopus Indexed	-
10	Incorporating Road Safety in Rural Road Network Level Pavement Management	100th Annual Meeting of Transportation Research Board, Washington DC (Presentation)	-	-