



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

Rathnathilaka Mudiyansele Kelum Sandamal

(198046R)

Degree of Master of Philosophy

Department of Civil Engineering

Faculty of Engineering

**UNIVERSITY OF MORATUWA - SRI LANKA**

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

Rathnathilaka Mudiyansele Kelum Sandamal

(198046R)

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

Department of Civil Engineering

University of Moratuwa

Sri Lanka

December 2021

## **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.

Signature: .....

Date: .....

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.

R. M. K. Sandamal,  
Department of Civil Engineering,  
University of Moratuwa.  
09.12.2021

## ACKNOWLEDGEMENTS

I need to pay my gratitude to the number of people for their help given to me in the completion of this study.

I especially pay my gratitude to **Dr. H. R. Pasindu**, Senior Lecturer of the Department of Civil Engineering, University of Moratuwa, who guided me throughout the whole period of the study and who provided me the academic environment necessary to achieve my research goals.

This research work could not have been completed without the financial support provided by **the SRC (Senate Research Council) of the University of Moratuwa** under the grant number SRC/LT/2018/19. Then, I wish to thank the support given by the Department of Civil Engineering, University of Moratuwa and its academic and non-academic staff members. **Prof. J. M. S. J. Bandara**, **Prof S.A.S. Kulathilaka** the previous Head of the Department and **Prof. C. Jayasinghe** the current Head of Department, was always given administrative support whenever necessary.

I would like to thank all of the lecturers in the Transportation Engineering Group in addition to my supervisor, **Prof. W. K. Mampearachchi**, **Dr. G. L. D. de Silva & Dr. Loshaka Perera**, who helped me both academically and during my time as a researcher.

Further, I would like to express my gratitude to my research progress evaluation committee members including **Dr. T.W.K. Ishani Dias** (Chairman of the panel), **Eng. R. M. Amarasekara** (Chairman of the panel), **Dr. J. C. P. H. Gamage** (Research coordinator), **Dr. A.S. Ranathunga** (Research Coordinator) who provided me extensive personal and professional guidance to improve my research findings.

Finally, I must thank all the people who helped me in many ways throughout the period of the study.

R. M. K. Sandamal,  
Department of Civil Engineering,  
University of Moratuwa.  
09.12.2021.

## **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



## TABLE OF CONTENTS

---

DECLARATION OF THE CANDIDATE & SUPERVISOR .....	i
DEDICATION .....	ii
ACKNOWLEDGEMENTS .....	iii
ABSTRACT.....	iv
LIST OF FIGURES .....	x
LIST OF TABLES .....	xii
LIST OF ABBRIVIATIONS .....	xv
1 INTRODUCTION .....	1
1.1 Introduction to the Road Network .....	1
1.2 Problem Statement .....	6
1.3 Research Objectives .....	7
1.4 Scope of the Research .....	7
2 LITERATURE REVIEW .....	11
2.1 Pavement Management Systems .....	11
2.1.1 Components of a Pavement Management System.....	13
2.1.2 Best Practices in Pavement Management .....	15
2.1.3 Pavement Management Systems Developed in Worldwide .....	16
2.2 Definition of Low Volume Roads.....	24
2.3 Pavement Condition Evaluation Techniques for LVRRs .....	25
2.3.1 The Relationship between IRI with Distresses .....	31
2.3.2 Smartphone-based Roughness Measurement .....	38
2.4 Prioritization Techniques in Pavement Management Systems .....	43
2.4.1 Worst First Approach.....	44
2.4.2 Direct Assessment Method .....	44
2.4.3 Evaluate Factors Using Goals .....	44
2.4.4 Reverse Prioritization.....	45
2.4.5 Analytical Hierarchical Process (AHP) .....	45
2.5 Optimization Techniques in Pavement Management Systems .....	46
2.5.1 Integer Programming .....	47
2.5.2 Dynamic Programming .....	47

2.5.3 Artificial Neural Networks (ANNs).....	47
2.6 Pavement Performance Evaluation & Maintenance Interventions .....	50
2.6.1 Work Intervention Criteria & Threshold for Maintenance Activities .....	51
2.7 Multi-objective Optimization Approach.....	58
2.8 Summary of the Chapter .....	63
<b>3 PAVEMENT CONDITION EVALUATION CRITERIA FOR LOW VOLUME ROADS</b>	<b>65</b>
3.1 Introduction to the Study Area.....	65
3.2 Relationship between Bump Integrator IRI and Smartphone-based Roughness Measurement.....	68
3.2.1 Data Collection .....	68
3.2.2 Establishing Relationship between Bump Integrator IRI vs Roadroid IRI.....	69
3.3 Relationship between IRI and Pavement Distress Condition .....	71
3.3.1 IRI vs Raveling .....	72
3.3.2 IRI vs Pothole .....	73
3.3.3 IRI vs Edge Breaking.....	74
3.3.4 IRI vs Edge Gap.....	74
3.4 Multiple Regression Analysis between IRI vs All Distress Types .....	76
3.4.1 Multiple Regression Model between IRI vs Distresses for Narrow Roads .....	78
3.4.2 Multiple Regression Model between IRI vs Distresses for Wider Roads .....	80
3.5 The Relationship between IRI vs PCI.....	82
3.6 The Relationship between IRI vs PSR.....	85
3.7 Development of Major Distress Repair Cost Estimation Model based on IRI.....	87
3.8 Identification of Maintenance and Rehabilitation Strategies for LVRRs.....	88
3.9 Summary of the Chapter .....	89
<b>4 FRAMEWORK OF SINGLE-OBJECTIVE OPTIMIZATION APPROACH:</b>	
<b>MAXIMIZATION OF OVERALL NETWORK CONDITION .....</b>	<b>90</b>
4.1 Introduction.....	90
4.2 Approach-1: Minimization of Average Network IRI using Integer Programming .....	91
4.2.1 Definitions of the Parameters.....	91
4.2.2 Formulation of Objective Function(s).....	92
4.2.3 Formulation of Constraint(s).....	92
4.2.4 Formulation of Decision Variable.....	93

4.3 Case Study: Maintenance Program using Integer Programming .....	95
4.4 Approach-2: Minimization of Average Network IRI using Genetic Algorithm.....	97
4.4.1 Formulation of Objective Function(s).....	98
4.4.2 Formulation of Constraint(s).....	98
4.4.3 Formulation of Decision Variable.....	98
4.5 Case Study: Maintenance Program using Genetic Algorithm .....	98
4.6 Comparison of Engineering Judgement with Proposed Optimization Approaches in Maintenance Decision Making .....	100
4.7 Summary of the Chapter .....	102
<b>5 MULTI-OBJECTIVE OPTIMIZATION APPROACH BY INCOPERATING SOCIO- ECONOMIC IMPORTANCE IN NETWORK-LEVEL DECISION MAKING .....</b>	<b>104</b>
5.1 Incorporating of Socio-Economic Importance in the Decision-Making Criteria .....	104
5.1.1 Identification of Socio-Economic Priority Factors .....	104
5.1.2 Formulation of Socio-Economic Importance Priority Index .....	105
5.2 Formulation of Multi-Objective Optimization Approach.....	107
5.2.1 Formulation of Secondary Objective Function .....	108
5.2.2 Utopia Point Method .....	111
5.2.3 Weighted Sum Method (WSM) .....	112
5.3 A Case Study to Illustrate the Proposed Multi-Objective Optimization Approach.....	113
5.4 A Case Study to Illustrate the Proposed Multi-Objective Optimization Approach by Incorporating Safety Performance.....	118
5.4.1 Formulation of Safety Performance as the Secondary Objective Function .....	118
5.5 A Case Study by Incorporating Safety Performance.....	119
5.6 Summary of the Chapter .....	124
<b>6 CONCLUSION .....</b>	<b>126</b>
<b>7 REFERENCES.....</b>	<b>129</b>
Appendix-A: Data Collection for Proposed Pavement Condition Criteria.....	xvii
Appendix-B: Road Network Details for Single Objective Optimization Approach.....	xxxvii
Appendix-C: Road Network Details for Multi-Objective Optimization Approach.....	xliv
Appendix-D: The List of Publications from the Dissertation .....	lix

## LIST OF FIGURES

Figure 2-1: Pavement Management System Process [12] .....	13
Figure 2-2: A Typical PMS Process [12].....	14
Figure 2-3: Decision-Aid Tool Components of Portugal PMS [16].....	17
Figure 2-4: Framework of the SLRAMS system [26] .....	23
Figure 2-5: IRI Ranges for Different Road Types of with Comfortable Speed Limits [40] ...	27
Figure 2-6: IRI Progression with the Cracking [56] .....	32
Figure 2-7: Plot of Arbitrary Pothole Values and the Corresponding Roughness Values for Sensitivity Analysis [51].....	33
Figure 2-8: Sample of Accelerometer Outputs for a Route with Different Pavement Conditions [74].....	40
Figure 2-9: Repeatability of Roadroid IRI on Highway Section I-75 [86].....	42
Figure 2-10: Relationship between Profiler and Roadroid Roughness on Highway Section I-75 North [86].....	42
Figure 2-11: The General Framework of Genetic Algorithm in Solving Optimization Problem .....	48
Figure 2-12: Asset Performance Curve for a Pavement Section in The Life Cycle.....	50
Figure 2-13: Pareto Front Concept and Finding the Optimal Set of Solutions from Bi-Objective Optimization .....	60
Figure 3-1: Example of Road Sections with Different Distress Levels in The Low Volume Rural Road Network .....	66
Figure 3-2: Vehicle Distribution of the Road Network .....	67
Figure 3-3: Cumulative Distribution of the Traffic Volume in the Network .....	67
Figure 3-4: Example of the Output IRI values from Bump Integrator .....	69
Figure 3-5: Comparison between Bump Integrator IRI vs Roadroid IRI .....	70
Figure 3-6: Plot of IRI vs Raveling Density .....	73
Figure 3-7: Plot of IRI vs Pothole Density .....	73
Figure 3-8: Plot of IRI vs Edge Breaking Density for Narrow Roads.....	74
Figure 3-9: Plot of IRI vs Edge Gap Percentage.....	75
Figure 3-10: Best Fitted Functions between IRI vs Distress Density .....	76
Figure 3-11: Regression Model Validation for Narrow Roads.....	80
Figure 3-12: Relationship between IRI and PCI.....	82
Figure 3-13: Relationship between PSR vs IRI .....	86

Figure 3-14: Cost Estimation Model for Major Distress Repair Concerning IRI.....	87
Figure 4-1: Analysis Scheme of the Proposed PMS for LVRRs .....	90
Figure 4-2: Pavement Management System Components .....	91
Figure 4-3: Decision-Tree Progression of Generic Constraints.....	93
Figure 4-4: Flowchart of Screening and Rehabilitation Process .....	94
Figure 4-5: The Framework of the Developed PMS using Genetic Algorithm.....	97
Figure 4-6: Comparison of Network Level Performance between Integer Programming vs Genetic Algorithm .....	100
Figure 4-7: Set of Feasible Solutions for the Case Study .....	101
Figure 5-1: Priority Factors in Socio-Economic Importance.....	105
Figure 5-2: The Analysis Procedure of Multi-Objective Optimization Approach .....	108
Figure 5-3: The Extended Decision Tree Progression for Different Pavement Type.....	109
Figure 5-4: Improvement of the Network Condition for Different Budgetary Scenarios .....	114
Figure 5-5: Comparison of Average Network IRI from Different Multi-Objective Optimization Methods.....	117
Figure 5-6: Comparison of Average Priority Road IRI from Different Multi-Objective Optimization Methods .....	117
Figure 5-7: Percentage Improvement of Pavement Condition in Various Budgetary Scenarios .....	122
Figure 5-8: Percentage Improvement of Safety Performance for Various Budgetary Scenarios .....	122
Figure 5-9: Pareto Fronts for Different Budgetary Scenarios.....	123
Figure 5-10: The Comparison of Condition and Safety Improvement between SOO Approach and MOO Approach.....	124
Figure A-1: Bump Integrator Calibration Graph for the Speed.....	xxiv

## LIST OF TABLES

Table 1-1: Percentage Increase of Total Vehicles, Heavy Vehicles and Road Length to the Base Year 2013 [2] .....	1
Table 2-1: Best Practices for Developing Countries [4] .....	15
Table 2-2: Summary of the Developed Pavement Management Systems Worldwide .....	21
Table 2-3: Threshold Value for Low Volume Road Definition in Worldwide .....	24
Table 2-4: IRI Scale vs Comfortable Speed for User [41].....	27
Table 2-5: The Characteristics of Equipment Used for the Pavement Condition Evaluation .	29
Table 2-6: Comparison of Network Level vs Project Level Data Types [49] .....	31
Table 2-7: Summary of Studies Conducted to Evaluate the Relationship between IRI and Distresses .....	36
Table 2-8: Roughness Measurement Equipment Classification [76] .....	38
Table 2-9: Summary of Results on Smartphone-Based Roughness Measurement.....	41
Table 2-10: Advantages and Drawbacks of Various Prioritization Methods [31].....	43
Table 2-11: Summary of Various Optimization Methods.....	49
Table 2-12: Pavement Performance Prediction Models Developed in Worldwide.....	51
Table 2-13: Characteristics of Pavement M&R Activities [116].....	53
Table 2-14: Possible Preventive Maintenance Treatments for Various Distress Types [117]	53
Table 2-15: M&R Practices for Each Strategy based on national Road Master Plan 2018 - 2027 [26].....	54
Table 2-16: Recommended M&R Threshold in Worldwide .....	55
Table 2-17: Road Maintenance Intervention for National roads with AADT<5000veh/day in Sri Lanka [134] .....	57
Table 2-18: Work Standards of RDA for Low Volume Roads [29].....	57
Table 2-19: Characteristics of Various Multiobjective Optimization Techniques [139] .....	61
Table 2-20: The Summary of the Recent Studies Addressing the Multi-Objective Problem in Pavement Management Systems.....	62
Table 3-1: Summary of Road Inventories in the Road Network .....	66
Table 3-2: Summary of Traffic Characteristic in the Rural Road Network.....	67
Table 3-3: Summary of Statistical Analysis of Fitted Line between Roadroid IRI and Bump Integrator IRI .....	70
Table 3-4: ANOVA Table of the Model.....	71
Table 3-5: Distress Classifications for Asphalt Concrete Pavement in ASTM D 6433-11.....	72

Table 3-6: Summary of IRI vs Distress Density Functions .....	76
Table 3-7: Correlation Matrix of Independent Variables (Distress) .....	77
Table 3-8: Statistical Summary of the Multiple Regression Model for Narrow Roads.....	78
Table 3-9: ANOVA Table of the Multiple Regression Model for Narrow Roads .....	78
Table 3-10: VIF values of the Multiple Regression Model for Narrow Roads .....	79
Table 3-11: Statistical Summary of the Multiple Regression Model for Wider Roads.....	81
Table 3-12: ANOVA Table of the Multiple Regression Model for Wider Roads.....	81
Table 3-13: VIF values of the Multiple Regression Model for Wider Roads .....	82
Table 3-14: Statistical Summary of the IRI vs PCI Model.....	83
Table 3-15: Categorization of Pavements In terms of IRI and PCI.....	84
Table 3-16: PSR description based on the FHWA interpretation.....	85
Table 3-17: Statistical Summary of the PSR vs IRI Model.....	86
Table 4-1: Types of M&R Actions .....	95
Table 4-2: Type of M&R Strategies .....	95
Table 4-3: Network Level Performance for Different Budgetary Levels.....	96
Table 4-4: Network Level Performance for Different Budgetary Levels.....	99
Table 4-5: Comparison of Solutions from Engineering Judgement, Integer Programming and Genetic Algorithm for Different Budget Levels .....	101
Table 5-1: Summary of Assignment of Scores for Attribute in Developing Priority Index [46] .....	106
Table 5-2: Types of M&R Actions used for Different Pavement Types.....	110
Table 5-3: Type of M&R Strategies in Different Pavement Types .....	110
Table 5-4: Summary of Results from Optimization Models for Different Scenarios.....	114
Table 5-5: Percentage of Road Lengths in each IRI Ranges for Different Budget Scenarios .....	115
Table 5-6: Anchor Points & Utopia Points for Different Budgetary Levels .....	115
Table 5-7: Results Obtained from Various Scenarios in Multi-Objective Optimization.....	116
Table 5-8: Anchor Points & Utopia Points for Different Budgetary Levels .....	120
Table 5-9: Selected Pareto Optimal Solutions from Various Scenarios in Multi-Objective Optimization .....	121
Table A-1: Summary of Inventory & Condition Data of Selected Road Network for the Study .....	xvii
Table A-2: Calibration Sheet of Bump Integrator .....	xxiii

Table A-3: A Sample Data Sheet Extracted from Roadroid Mobile Application .....	xxv
Table A-4: Roughness Value from Bump Integrator and Roadroid Mobile App.....	xxvi
Table A-5: Road Details and Estimated IRI Values for Narrow Roads Multiple Regression Model Validation .....	xxix
Table A-6: The Road Prioritization Ranking in IRI and PCI Basis.....	xxxii
Table B-1: Summary of Road Inventory for Rathnapura PRDA Road Network .....	xxxvii
Table B-2: Selected M&R Program under Rs.100 Million Budget Level using Integer Programming.....	xxxviii
Table B-3: Selected M&R Program under Rs.100 Million Budget Level using Genetic Algorithm.....	xxxix
Table B-4: The Hypothetical Road Network for Case Study .....	xl
Table B-5: Summary of Engineer's Response for the Case Study.....	xli
Table C-1: Summarization of Literature Analysis to Establish the Intervention Levels used in the Analysis Scheme .....	xliv
Table C-2: Road Inventory Data and Priority Index Data of Case Study Network-Negombo .....	xlvi
Table C-3: Selected Maintenance Strategies for Each Road Segment in Three Different Budgetary Levels .....	lii
Table C-4: Road Inventories Collected for the Case Study Incorporating Safety Performance .....	lviii
Table D-1: List of Publications from the Dissertation.....	lix



## **LIST OF ABBRIVIATIONS**

<b>Abbreviation</b>	<b>Description</b>
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