MANAGING ROAD NETWORKS ACCESSIBILITY TO COPE WITH EXTREME WEATHER CONDITION IN DEVELOPING COUNTRIES

by

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ABSTRACT

It is essential to understand the effects of climate change in the transportation sector because these consequences can lead to severe problems of accessibility and damage to road infrastructure. The effects of climate change reduce access to the road network and cause the deterioration of transport infrastructure. A road asset management regime should ensure that all locations are accessible and connected to the network. Failure to maintain accessibility across the road network hampers social-economic development and increases poverty. The accessibility problem has been addressed by models which, to date, have not explicitly considered the life cycle of the road infrastructure. Therefore, this research develops such a procedure and examines how climate change and extreme weather conditions affect road accessibility.

This research developed an infrastructure-based accessibility model with Indonesia as an example and includes maintenance standards and strategies for managing road assets under extreme weather conditions. The model, which was tested extensively, describes accessibility in terms of availability, quality, and reliability of access. Standards and strategies for Indonesia were evaluated using HDM-4, which is the standard decision support tool for road asset management. It was found that the existing standards are adequate to sustain current levels of accessibility. However, to improve accessibility, the gravel roads must be upgraded into sealed roads, and new roads should also be built. The methodology and conclusions of this research could assist road authorities in managing road infrastructure under budget constraints, and subsequently, support regional development through improved accessibility.

Keywords: climate change, extreme weather, accessibility model, road asset management, HDM-4, regional development.

DEDICATION

To my beloved wife, Zulfa Budiastuti,
and kids, Nadya Izza Kamila and Muhammad Iqbal Afkari.

To my parents
Sungaib Rizal and Maslikhatun

and

To my parents-in-law
Slamet Riyanto and Siti Rahayu Rachmawati

"Thank you for all your support during my PhD study,
thank you for being my strength and reason to keep fighting
for pursuing my dreams"

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TABLE OF CONTENTS

CHAPTER 1 INTRODUCTION 1

1.1 Introduction 1

1.2 Research Question 3

1.3 Research Aim and Objectives 3

1.3.1 The Aim of the Research 3

1.3.2 Objectives of the Research 3

1.4 Research Scope and Limitation 4

1.5 Research Outcome 4

1.6 Innovative Features of the Research 4

CHAPTER 2 LITERATURE REVIEW 5

2.1 Introduction 5

2.2 Accessibility 5

2.2.1 Definition of Accessibility 5

2.2.2 Components and Factors Influencing Accessibility 6

2.2.3 Accessibility Measurement 9

2.2.4 Accessibility in Developing Countries 10

2.3 Climate Change and Extreme Weather Events (EWEs) 12

2.3.1 Definition of Climate Change and EWEs 12

2.3.2 Climate Projection and Scenario 14

2.3.3 Climate Impact on Road Networks Infrastructure 16

2.4 Summary 19

CHAPTER 3 METHODOLOGY 20

3.1 Introduction 20

3.2 Overall Approach 20

3.3 Supporting Regional Development through Infrastructure-based Accessibility 24

3.4 Development of Accessibility Model 26

3.4.1 Definition of Accessibility 26

3.4.2 The Concept of Equity in Accessibility Model 27
3.4.3 Accessibility to Link Communication Between Stakeholders 27
3.4.4 Method for Developing Accessibility Model 28
3.5 Climate Change Adaptation 29
3.6 The HDM-4 Economic Analysis 31
3.7 Summary 32

CHAPTER 4 CLIMATE CHANGE IN INDONESIA AND ITS IMPACT ON ROAD CONDITIONS 33
4.1 Introduction 33
4.2 Indonesia as the Case Study for Developing Countries 33
4.2.1 Country Profile 33
4.2.2 Road Asset Management in Indonesia 35
4.2.3 Climate and Weather in Indonesia 37
4.3 Climate Change and Extreme Weather Scenario 40
4.4 The Impact of Changes in the HDM-4 Climate Parameters on Road Conditions 42
4.4.1 Climate Parameters in the HDM-4 42
4.4.2 The Scenario of Changing in Climate Parameter 43
4.4.3 Road Representatives 43
4.4.4 The Impact of Precipitation on Road Condition 44
4.4.5 The Impact of Temperature on Road Condition 47
4.4.6 The Impact of Other HDM-4 Climate Parameters on Road Condition 50
4.5 Simulation of Climate Change Scenarios in the HDM-4 52
4.5.1 Road Representatives 52
4.5.2 Approach to Simulate Climate Change Scenario in the HDM-4 52
4.5.3 The Application of Static and Dynamic Climate Input in the HDM-4 Model 53
4.6 Summary 56

CHAPTER 5 DEVELOPMENT OF ROAD NETWORK ACCESSIBILITY INDEX 58
5.1 Introduction 58
5.2 Overall Approach 58

5.3 Step 1: Theoretical Framework of the RNAI Model 59
5.3.1 Aims and Definition of the RNAI Model 59
5.3.2 Units of Analysis 60
5.3.3 Conceptual Design of the RNAI Model 60
5.4 Step 2: Selection of Indicators 63
5.5 Step 3: Data Treatment 65
5.5.1 Missing Values 66
5.5.2 Data Outliers 66
5.6 Step 4: Multivariate Analysis 66
5.7 Step 5: Normalisation 67
5.7.1 The Base Form of Accessibility Components 68
5.7.2 Normalisation Technique 69
5.8 Step 6: Weighting and Aggregation 72
5.9 Interpretation and Visualisation of the Accessibility Index (RNAI) 75
5.9.1 Interpretation of the RNAI 75
5.9.2 Visualisation of the RNAI 76
5.10 Summary 77

CHAPTER 6 MODEL TESTING 80
6.1 Introduction 80
6.2 Application of the RNAI Model in Indonesia 80
6.2.1 Defining the Unit of Analysis 81
6.2.2 Data Characteristic 81
6.2.3 Correlation Analysis 86
6.2.4 Quantification of the RNAI Model 88
6.3 Step 7: Robustness Test for the RNAI Model 92
6.3.1 Uncertainty in the Combination of Input Variables 92
6.3.2 Robustness of the RNAI Formula 94
6.4 Accessibility Relative to International Benchmark 97
6.5 Summary 99

CHAPTER 7 SENSITIVITY AND SCENARIO ANALYSIS 101
7.1 Introduction 101
7.2 Sensitivity Analysis 102
7.2.1 Regression Analysis 102
7.2.2 One-at-a-time (OAT) Sensitivity Measures 104
7.2.3 Monte Carlo Simulation 106
7.2.4 Quantification formula of the RNAI model 110
7.3 Scenario Analysis 111
7.4 Summary 115

CHAPTER 8 MODEL APPLICATION: DEVELOPING STANDARDS AND STRATEGIES TO MANAGE ROAD NETWORKS ACCESSIBILITY 117
8.1 Introduction 117
8.2 Linking Accessibility Model with Road Asset Management Tool (HDM-4) 117
8.3 Road Asset Database 119
8.3.1 Profile of Kalimantan Selatan Province 119
8.3.2 Road Asset in the Kalimantan Selatan Province 120
8.4 The Impacts of Road Asset Management Regime on Accessibility (Unconstrained Budget Scenario) 121
8.4.1 Optimisation Method in the HDM-4 121
8.4.2 Life Cycle Cost Analysis (LCCA) on Accessibility Improvement Scenarios 123
8.4.3 Accessibility Management by Optimising the Existing Road Assets 125
8.4.4 The Overall Picture of Accessibility Development in Kalimantan Selatan Province 130
8.5 The Impacts of Budget Scenario on Road Condition and Accessibility 131
8.6 The Impact of Climate Change on Accessibility 134
8.7 The Impact of Extreme Weather on Accessibility 136
8.8 Adaptation Standards and Strategies 139
8.8.1 Adaptation Standards 139
8.8.2 Accessibility Management Strategies 140

CHAPTER 9 DISCUSSION 144
9.1 Introduction 144
9.2 The Road Network Accessibility Model (RNAI) 144
9.2.1 General Concept and Development of the RNAI 144
9.2.2 Contributing Factors Included in the Accessibility Models 147
9.2.3 Relationship Between Accessibility Components 149
9.2.4 Transferability 149
9.3 Comparison of the RNAI Model with the World Bank Model 151
9.4 Accessibility Management to Cope with Climate Change and Extreme Weather 155
9.4.1 Method for Representing Climate Change and Extreme Weather Scenario in HDM-4 155
9.4.2 Climate Change and Extreme Weather Adaptation in Accessibility Management 156
9.4.3 General Scheme for Accessibility Management 158
9.5 The Use and Impact of Accessibility Management in Indonesia 159
9.5.1 Accessibility as a Tool to Strengthen the National Integrity and Regional Development 159
9.5.2 The Use of the RNAI Model to Anticipate Latent Impact of Accessibility Development 162

CHAPTER 10 CONCLUSIONS AND FURTHER WORK 163
10.1 Conclusions 163
10.2 Further Work 166

REFERENCES 168

LIST OF APPENDICES

APPENDIX A ACCESSIBILITY REVIEW A-1
A.1 Definition of Accessibility A-1
A.2 Measurement of Accessibility Model A-2

APPENDIX B CASE STUDY B-1
B.1 Data Requirement of This Research B-1
B.2 Maps of Indonesia and Kalimantan Selatan Province B-2
B.3 Characteristic or Road Asset in Indonesia B-4
B.4 Road Asset Maintenance Standards in Indonesia B-4
B.5 The HDM-4 Input B-5
B.6 HDM-4 Calibration Factor Road Maintenance Standards in Indonesia B-16

APPENDIX C THE ROAD NETWORK ACCESSIBILITY INDEX (RNAI) C-1
C.1 Definition C-1
C.2 Goal and Objectives C-1
C.3 Unit of Analysis C-1
C.4 Components C-2
C.5 Quantification C-2
C.6 Presentation and visualisation of RNAI C-3
C.7 Interpretation of the RNAI Value C-5
C.8 Model Limitation C-6
C.9 Innovative Features of the RNAI model C-6

APPENDIX D HDM-4 ..... D-1
D.1 HDM-4 Inputs D-1
D.2 HDM-4 Outputs D-5

APPENDIX E PUBLICATION..... E-1

E.1 The 7th International Conference on Bituminous Mixtures and Pavements [7th ICONFBMP], Thessaloniki, Greece, 12-14 June 2019 ..... E-1

E.2 2nd Annual SoE PGR Symposium, The University of Birmingham, Birmingham, UK, 16th July 2018 ..... E-14

E.3 Student conference 2016, The University of Birmingham, Birmingham, UK E-19

LIST OF FIGURES

Figure 1.1 Accessibility problem induced by extreme weather 2
Figure 2.1 The benefit of accessibility improvement for better opportunities and travel freedom (modified from Odoki et al., 2001; Junoasmono, 2004) 8
Figure 2.2 Climate change impact on global temperature and mean sea level (after IPCC, 2014a) 15
Figure 2.3 The multi-models of IPCC climate projection for simulating the extent of permafrost in the Northern Hemisphere (after Settele et al., 2015)..... 16
Figure 2.4 The potential impacts of extreme weather events (EWEs) on accessibility..... 17
Figure 3.1 Inclusion of accessibility criterion to manage road networks accessibility..... 22
Figure 3.2 Accessibility model to link accessibility with road management and climate . 22
Figure 3.3 The world by the income year 2014 (based on World Bank database, 2019).. 24
Figure 3.4 Intervention of road infrastructure investment on transport land-use feedback cycle (adapted from Wegener and Fürst, 1999; Bertolini, 2012) 25
Figure 3.5 Investment approach in road infrastructure 26
Figure 3.6 The concept of equity in road infrastructure..... 27
Figure 3.7 Accessibility model to link communication between stakeholders..... 28
Figure 3.8 Attributes contributing to accessibility model..... 29
Figure 3.9 Adjusting climate change inputs on the HDM-4 tool..... 30
Figure 3.10 Calculation of road project benefits during the budget period (after Kerali et al., 1998) 31
Figure 4.1 The map of Indonesia as a case study..... 34
Figure 4.2 Road assets in Indonesia..... 35
Figure 4.3 Typical road conditions in Indonesia..... 35
Figure 4.4 Road authority scheme and responsibility in Indonesia 36
Figure 4.5 Road category based on function in Indonesia..... 36
Figure 4.6 User interface of IRMS database..... 37
Figure 4.7 Historical weather pattern in Indonesia in the last decade (after BMKG, 2018b)..... 38

Figure 4.8 Extreme anomalous in air temperature seen in 2016 against data from 1981-2010 (after BMKG, 2019) 39
Figure 4.9 Number of disasters in Indonesia 39
Figure 4.10 Historical data and projection scenario of annual temperatures in Indonesia.. 40
Figure 4.11 Historical data and projection scenario of annual precipitation in Indonesia .. 41
Figure 4.12 Altering climate parameters inputs in the HDM-4 tool 43
Figure 4.13 The impact of changes in precipitation on bituminous road conditions 44
Figure 4.14 The impact of changes in precipitation parameter on gravel road conditions . 45
Figure 4.15 Deterioration scheme of bituminous road influenced by precipitation in the HDM-4 (resumed from HDM-4 manual, Morosiuk et al., 2004)..... 46
Figure 4.16 Deterioration scheme of gravel road influenced by precipitation in the HDM-4 (resumed from HDM-4 manual, Morosiuk et al., 2004)..... 46
Figure 4.17 The impact of temperature changes on road conditions..... 48
Figure 4.18 Pavement parameters as HDM-4 inputs..... 49
Figure 4.19 Changes in the number of days when the temperature exceeds 32 0C 50
Figure 4.20 Changes in the percentage of driving done on water covered roads..... 50
Figure 4.21 Integral theorem in calculating the area below a curve..... 53
Figure 4.22 Scenario of splitting the period for changing climate parameters..... 53
Figure 4.23 Road condition Vs approach of climate change input in HDM-4..... 55
Figure 5.1 Procedure to develop composite indicator model (adapted from Nardo et al., 2008)..... 59
Figure 5.2 The RNAI measurement focuses on road infrastructure features..... 60
Figure 5.3 Components of the RNAI model 63
Figure 5.4 Normalization of accessibility components..... 72
Figure 5.5 Interface of QGIS software..... 77
Figure 6.1 Identification of data outliers..... 81
Figure 6.2 Accessibility component in Indonesia based on provinces of the year 2014 ... 82
Figure 6.3 Distribution of accessibility index in Indonesia using the scenario of with and without threshold value..... 96
Figure 6.4 Distribution of worldwide road density..... 98
Figure 6.5 Accessibility index in Indonesia relative to international benchmark..... 99

Figure 7.1 The output of multiple regression analysis using the SPSS software 104
Figure 7.2 One-at-a-time (OAT) sensitivity measures for the RNAI model 105
Figure 7.3 The typical output of sensitivity analysis using Monte Carlo simulation 108
Figure 7.4 The impact of change in accessibility component using scenario analysis 113
Figure 8.1 Framework to link the RNAI model with HDM-4 118
Figure 8.2 Kalimantan Selatan Province (after Pta-banjarmasin, 2018) 119
Figure 8.3 Distribution of road category in Kalimantan Selatan Province in 2014 120
Figure 8.4 Road network condition Vs HDM-4 optimisation method (unconstrained budget) 122
Figure 8.5 Accessibility Vs HDM-4 optimisation methods (unconstrained budget) 122
Figure 8.6 Accessibility improvement using Do Minimum as the base option (based on the sensitivity analysis scenario in Table 7.5, Chapter 7.3) 124
Figure 8.7 Accessibility development using IRMS standards as the base options 125
Figure 8.8 Road condition Vs Scenario of accessibility development using IRMS standards as the base options (unconstrained budget) 125
Figure 8.9 Accessibility optimisation scenarios using the existing road asset 127
Figure 8.10 Road network condition using existing IRMS maintenance standards 128
Figure 8.11 Road network condition based on surface class 128
Figure 8.12 Budget requirement Vs Road maintenance scenarios (unconstrained budget) 129
Figure 8.13 The impact of road asset management regime on the accessibility components 131
Figure 8.14 Road condition Vs budget constraint by optimising the existing road assets .. 133
Figure 8.15 Accessibility Vs Budget constraint by optimising the existing road assets 133
Figure 8.16 Climate scenario Vs Road network conditions 134
Figure 8.17 Climate scenarios Vs Accessibility 135
Figure 8.18 Climate scenarios Vs Budgetary requirement 135
Figure 8.19 Road degradation scenario Vs accessibility index 137
Figure 8.20 Road degradation scenario Vs road conditions 138
Figure 8.21 The impact of road degradation scenarios on the maintenance budget 138
Figure 8.22 The impact of updating gravel road maintenance standards on accessibility (unconstrained budget) 139

Figure 8.23 The impact of updating gravel road maintenance standards on road conditions and budgetary requirement (unconstrained budget)..... 140
Figure 8.24 Proposed strategies to managed accessibility 142
Figure 8.25 General scheme to enhance accessibility level in Indonesia..... 142
Figure 9.1 Relationship between the RNAI components..... 149
Figure 9.2 Accessibility Vs Economic Development Indicator in Indonesia by province 152
Figure 9.3 Accessibility Vs Economic welfare and prosperity..... 153
Figure 9.4 Accessibility Vs Population density by the province in Indonesia 154
Figure 9.5 Indonesia moving the capital to ensure equity distribution in development and avoid extreme climate events risk..... 161

LIST OF TABLES

Table 2.1 Various components and constraints in the current accessibility models..... 7
Table 2.2 Various types of accessibility measurement and point of view..... 10
Table 2.3 The threshold of extreme weather parameters in Indonesia 14
Table 2.4 The potential impact of climate change and extreme weather on the condition of road assets and accessibility in tropical countries 18
Table 4.1 Comparison of road category in Indonesia with other countries 37
Table 4.2 The default value of climate parameter in HDM-4 version 2..... 42
Table 4.3 Scenarios for changing climate parameters 43
Table 4.4 Type of distress in the HDM-4 models influenced by climate parameters 46
Table 4.5 The value of environmental coefficient 'm' in HDM-4 version 2 47
Table 4.6 Scenario of splitting the climate change period..... 54
Table 4.7 Road condition parameters at the end of each 5-year analysis 54
Table 5.1 Data characteristics of accessibility indicators 64
Table 5.2 RNAI components and the link to the HDM-4 as a road appraisal tool..... 65
Table 5.3 The strengths and weaknesses of selected accessibility indicators 65
Table 5.4 Assessment of normalisation methods for the RNAI model 67
Table 5.5 Individual form of accessibility components..... 68
Table 5.6 Technique to normalize the RNAI component 69
Table 5.7 Assessment of several weighting methods for the RNAI model 73
Table 5.8 The RNAI value and meaning 76
Table 5.9 Comparison of alternative models to quantify the RNAI 78
Table 6.1 Test of normality..... 84
Table 6.2 The pattern of accessibility components in Indonesia year 2014 85
Table 6.3 Descriptive statistic of accessibility components in Indonesia year 2014..... 85
Table 6.4 Correlation test for the RNAI components using a scatter plot..... 87
Table 6.5 Pearson's correlation test for the RNAI components 87
Table 6.6 The threshold and formula for the model $M3$..... 89
Table 6.7 The value of accessibility components in Indonesia based on provinces for 2014 90

Table 6.8 Accessibility in Indonesia based on provinces in the year 2014 91
Table 6.9 The value of the accessibility index and its components in Indonesia 92
Table 6.10 Robustness test of accessibility model using extreme values 93
Table 6.11 Adjustment of formula in the RNAI model..... 96
Table 6.12 The resume of the robustness test outcomes 97
Table 6.13 Calibration factor for different countries and benchmarks..... 98
Table 7.1 Best fit distribution of the RNAI components using Indonesian data in the year 2014 107
Table 7.2 Sensitivity report of Monte Carlo (MC) simulation based on distribution input 109
Table 7.3 The components of accessibility measure (RNAI) in Indonesia in the year 2014 109
Table 7.4 The results of sensitivity analysis 111
Table 7.5 The scenario and theoretical impacts of changes in the RNAI components 112
Table 7.6 Scenario of changes in input for accessibility index 112
Table 7.7 Road management impact on accessibility (RNAI) 114
Table 7.8 Road degradation impact on accessibility (RNAI)..... 114
Table 8.1 Categorized length of the road network in Kalimantan Selatan province in the year 2014 (km)..... 121
Table 8.2 Road conditions and budget requirement based on HDM-4 optimisation methods..... 123
Table 8.3 Scenario of a gradual upgrade of gravel roads in the Kalimantan Selatan province 126
Table 8.4 Constrained budget scenario using the IRMS standards [M+I] 132
Table 8.5 The scenario of a constrained budget 132
Table 8.6 Climate change scenario 134
Table 8.7 Road degradation scenario due to extreme weather events 137
Table 9.1 Regional proliferation in Indonesia (after Indonesian Ministry of Home Affairs, 2019)..... 161

LIST OF DEFINITIONS

Accessibility	:	the ease to reach destination(s).
Climate	:	the general weather conditions usually found in a particular place, e.g. rainfall, temperature, humidity
Climate Change	:	a long-term shift in weather patterns across the world.
Equity	:	equal treatment; fairness, i.e. the need for fairness both in the distribution of benefits or losses and in the entitlement to a high-quality standard of living
Extreme Weather	:	severe weather conditions which differ significantly from typical weather patterns.
Information Quality Level (IQL)	:	the quality of the content of information systems which corresponds to the degree of sophistication, and methods of data collection and processing used and the decisions supported. The IQL is a concept developed by the World Bank to link the amount of information detail with the level of decision supported in road asset management.
International Roughness Index (IRI)	:	a standard measurement of riding comfort, measuring longitudinal smoothness of road pavement (in the direction of driving).
Region	:	an area (any unit of space) that has shared features/characteristics but not always fixed boundaries. A regional area can be grouped based on physical features, such as an island, or based on an administrative area, such as province, regency, or village.
Reliability of model	:	the degree to which the output of the model can be interpreted consistently by providing year-round accuracy for varying climatic situations and scenarios.
Road Network Accessibility Index (RNAI)	:	the extent to which road network infrastructure ease road users to reach their destination(s) throughout the year within a particular region.

ABBREVIATIONS

AASHTO	:	Association of American State Highway and Transportation Officials
AI	:	Accessibility Index or Accessibility Indicator
ARIA	:	Accessibility/Remoteness Index of Australia
ASTM	:	American Standard Testing and Material
BCR	:	Benefit Cost Ratio
BMKG	:	Badan Meteorologi, Klimatologi, dan Geofisika; The Indonesian Non-Departmental Government Agency for Meteorology, Climatology, and Geophysics
BPS	:	Badan Pusat Statistic, The Indonesian Central Bureau of Statistics
EWEs	:	Extreme Weather Events
GDP	:	Gross Domestic product
GHG	:	Greenhouse Gas
HDM-4	:	Highway Development and Management 4th generation
IDR	:	Indonesian Rupiah
IPCC	:	The Intergovernmental Panel on Climate Change
IQL	:	Information Quality Level
IRAP	:	Integrated Rural Accessibility Planning
IRI	:	International Roughness Index
IRMS	:	Indonesian Integrated Road Management System
LCCA	:	Lifecyle Cost Analysis
NPV	:	Net Present Value
OECD	:	The Organisation for Economic Co-operation and Development (OECD
RAC	:	Road Agency Cost
RAI	:	Rural Accessibility Index
RCP	:	Representative Concentration Pathways
RNAI	:	Road Networks Accessibility Index
RUC	:	Road User Cost
SDI	:	Surface Distress Index (visual)
WMAPT	:	Weighted Mean Asphalt Pavement Temperature

CHAPTER 1

INTRODUCTION

1.1 Introduction

Infrastructure plays an essential role in supporting regional activities for social-economic development (Rietveld and Bruinsma, 2012). Developing a proper road infrastructure enhances connections to different locations, mainly peripheral areas so that the regional accessibility is increased (Komornicki, 2014). A higher level of accessibility within an area gives the residents more opportunity to engage in social and economic activities because it reduces transportation costs and increases their social interactions (Vickerman et al., 1999; Ma'ruf, 2014).

Accessibility is known as the "ease level to reach desired services, activities, or destinations" (Geurs et al., 2016). Failure to maintain accessibility along the road networks hampers economic development and increases poverty. Developing countries, which are characterised by poor road conditions and limited budgets, have long struggled with accessibility issues (Dingen, 2000). Nevertheless, climate change, through its extreme weather, worsens the condition of road infrastructure (Meyer, 2006; Meyer et al., 2013).

Global climate change has become a big issue in recent decades (OECD, 2015a). In terms of pavement engineering, it is noted that climate change causes severe problems in road infrastructure due to higher temperatures, precipitation, and other natural hazards (IPCC, 2014a). Through extreme weather events (EWEs), climate change causes damage and shortens the life of pavements, which require more frequent road maintenance, repairs, and rehabilitation (see **Figure 1.1**). Consequently, it increases the total cost of road asset management (Koetse and Rietveld, 2009; Kodippily et al., 2018).

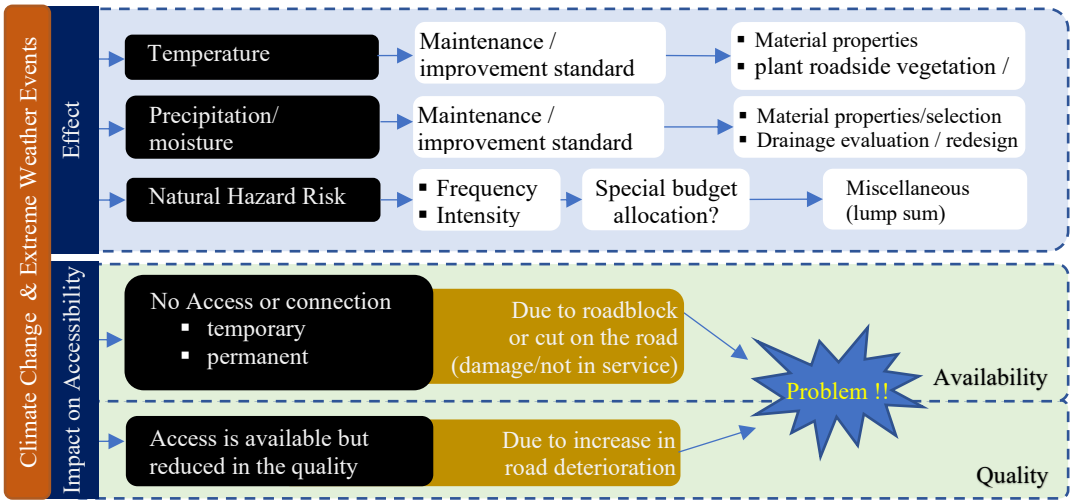


Figure 1.1 Accessibility problem induced by extreme weather

In term of accessibility, EWEs can affect road performance and even cut access to roads because they lead to the faster deterioration of roads or cause instant damage (Chapman, 2015; Kleinfelder, 2015). Reduced road access, such as delays or reductions in travel speed due to poor road conditions, increases the travel cost and limits the opportunities individuals have to perform activities (Litman, 2016). Meanwhile, zero accessibility, which occurs when roads and bridges are blocked due to landslides or flooding, restricts people`s access to essential services such as hospitals, markets, and water resources (Gulyás and Kovács, 2016; Xiao et al., 2016). Usually, the problem of accessibility can be solved by proper engineering and management approaches (Rattanachot et al., 2015; ITF, 2016). However, just developing new maintenance and design standards as an engineering countermeasure to cope with extreme weather is not sufficient because the existing accessibility measures do not directly address the issue of road accessibility. To date, there have been several accessibility models used to examine road network accessibility levels. However, most do not directly consider the condition of road infrastructure and its lifecycle (see **Chapter 2**). Therefore, there is a need for an enhanced accessibility model, which coupled with a lifecycle analysis of road assets may offer a definition of sustainable standards and strategies to enable optimum level of accessibility.

1.2 Research Question

The following questions elaborate further on the above innovative approach.

a. How may extreme conditions affect the accessibility of road networks?
b. How should road networks accessibility be managed to cope with climate change and extreme weather conditions?
c. How may an accessibility model be linked with an economic decision support tool, e.g. HDM-4 software, in managing road network accessibility?

1.3 Research Aim and Objectives

1.3.1 The Aim of the Research

This research aims to find out how road network accessibility should be managed to cope with extreme weather conditions in a sustainable manner. By linking accessibility with road economic optimisation, road managing authorities may offer equitable levels of accessibility across regions; leading to increased national social-economic development.

1.3.2 Objectives of the Research

The specific objectives are as follows:

a. Investigate how climate change affects road asset infrastructure and its impact on accessibility.
b. Develop a road infrastructure-based accessibility model that has the potential for use to promote regional development.
c. Develop maintenance standards and strategies that enable an optimum level of accessibility under changing climate conditions, using Indonesia as a case study.
d. Demonstrate the practical usefulness of the model in road asset management and in addressing the problem of accessibility.

1.4 Research Scope and Limitation

The above topic appears to extend beyond the scope work of this PhD. Therefore, the following apply:

a. The developed accessibility model only focuses on road infrastructure and does not explicitly consider road traffic and land use component.
b. The accessibility model and the adaptation standards and strategies were developed using Indonesia as the case study. However, the model may be adaptable for other countries after some adjustments.

1.5 Research Outcome

The outcome of this research is a road infrastructure-based accessibility model (RNAI) together with road maintenance standards and strategies to cope with extreme weather conditions.

1.6 Innovative Features of the Research

Innovative features and contributions of this research are:

a. The development of the accessibility model, considering the concept of equity on the availability and condition of road infrastructure to promote regional social-economic development.
b. Linking the concept of accessibility with climate change and road asset management.
c. The development of a methodology of road maintenance standards and strategies which enables optimum level of accessibility under changing climate conditions.
d. The development of a simple model to link the communication between stakeholders in managing road network accessibility.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

This chapter presents a literature review on accessibility and climate change in developing countries. This research investigates how road accessibility should be managed under climate change and its extreme weather conditions, so it is necessary to conduct a literature review on recent accessibility models to assess the strengths and weaknesses in the theory and application. Furthermore, it investigates how the new accessibility model should be developed to address the existing weaknesses, e.g. concerning climate change exposure.

This chapter consists of four sections. First, the various approaches and definitions of accessibility are explored, along with the components and factors that influence the level of accessibility. Afterwards, the current accessibility model and the best practice application in developing countries are reviewed. Also, the accessibility measurement in Indonesia is evaluated. The sections evaluate climate change and extreme weather events, including how future climate should be estimated and its potential impact on the condition of road networks and accessibility.

2.2 Accessibility

2.2.1 Definition of Accessibility

The concept of accessibility has been widely used in several fields of study, such as urban planning, transportation geography, marketing, and general welfare studies (Geurs and Wee, 2004; Litman, 2016). Accessibility has different meanings depending on the approach and context. The very fundamental question is how the term accessibility should be defined and

measured, and the answer to this question is vital because it affects the overall concept and direction of the research. According to El-Geneidy and Levinson (2006), the term accessibility is derived from the words "access" and "ability". Coming from the Latin word *accedere,* "access" means "to come" or "arrive". Together, accessibility means the ability to access or approach something. Thus, based on previous studies (Hansen, 1959; Ingram, 1971; Dalvi and Martin, 1976; Ben-Akiva and Lerman, 1979; Burns, 1979; U.S. Department of the Environment, 1996; Odoki et al., 2001; Berdica, 2002; Geurs and Wee, 2004), the concept of accessibility is generally defined as the "ease of reaching destination(s)". However, because it can be addressed both qualitatively or quantitatively, the interpretation of the term "ease" is broad depending on the context of the application (see **Appendix A**).

In recent decades, the approach of accessibility has typically focused on the 'opportunity of activities at the destination' and 'travel impedance' as the main features. A high level of accessibility is achieved when there are more travel options (routes, modes) and less travel impedance (distance, time, cost, and effort) to reach possible destinations (Geurs et al., 2016). Indisputably, a high level of accessibility cannot be achieved without proper road network infrastructure. When considering an infrastructure-based accessibility approach, Berdica (2002) defined accessibility as "the serviceability of a link/route/road network describes the possibility to use that link/route/road network during a given period." Meanwhile, a more comprehensive definition comes from Geurs and Wee (2004) who defined accessibility as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations using a (combination of) transport mode(s)".

2.2.2 Components and Factors Influencing Accessibility

Accessibility is a fundamental concept influenced by many factors and perspectives. Burns (1979) and Odoki et al. (2001) pointed out that accessibility is typically measured based on

three main components which are land use (spatial), transportation (infrastructure and services), and travel constraint. In theory, accessibility should at least consider the transport system and land-use as the main components (Hansen, 1959; Ingram, 1971; Ben-Akiva and Lerman, 1979). However, different people at the same location may evaluate accessibility differently if their needs and preferences vary (Burns, 1979; Handy and Niemeier, 1997). In practice, the concept of accessibility is not always associated with a distance factor, but with the "ease" to reach an opportunity or location(s). Other studies, e.g. from Odoki et al. (2001) and Geurs and Wee (2004), suggested that accessibility components should include temporal and social-economic-cultural constraints. Also, due to the rapid development of information and communications technology (ICT), there have been drastic changes in travel behaviour. The use of ICT is an inevitable part of daily life in many ways, especially for people who live in large cities or developed countries. Some people consider it as a substitute for travel which influences the accessibility level of an area or region (Wee, 2016). The summary of components and constraints of accessibility models can be seen in **Table 2.1**.

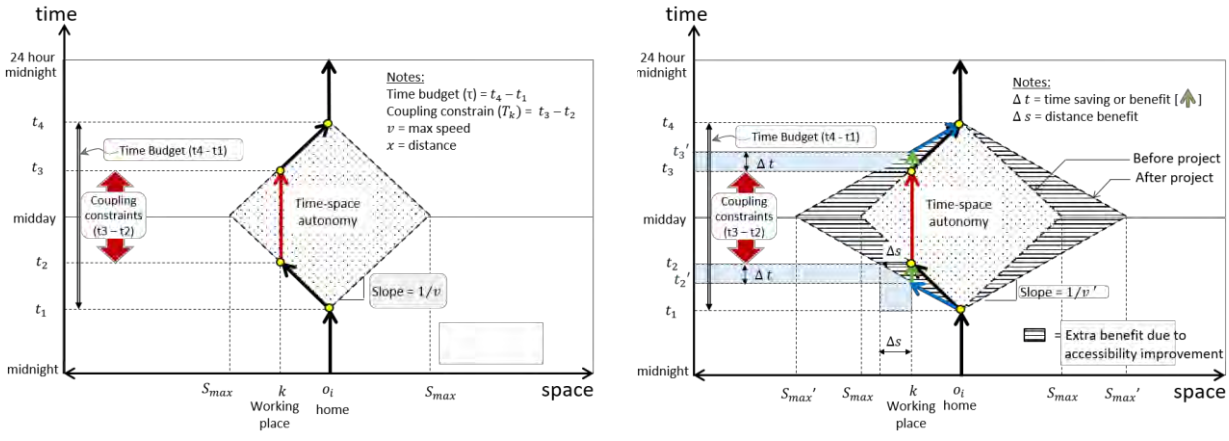
Table 2.1 Various components and constraints in the current accessibility models

Accessibility Component		Consideration	Example of measurement indices [a]
Land-use (spatial)		▪ destination opportunities (supply) ▪ origin potential (demand) ▪ the confrontation of demand and supply for opportunities ▪ Separation of locations	▪ number of jobs, schools, hospitals, shops, social facilities ▪ number of households or populations ▪ number of jobs and school vacancies or hospital beds ▪ travel distance
Transportation		▪ Road infrastructure ▪ vehicle fleet, public transport ▪ travel impedance or disutility	▪ road density, level of services ▪ number of public transports, route, headway ▪ travel time, travel costs
Travel constrain	Temporal	▪ travel time, ▪ coupling constraint ▪ total time budget	▪ minutes per km travelled ▪ working hours or school hours ▪ time budget 16 hours per day
	Individual	▪ economic ▪ social ▪ cultural	limited access due to age, gender, cultural rules, income, and individual's physical condition
	Information and Communication Technologies (ICT)	activity substitute such as e-work, e-shopping or e-learning	▪ telecommunication network coverage ▪ internet services, gadget ownership ▪ human behaviour

a. Resumed based on Miller (2018), Wee (2016), Moustou et al. (2015) Geurs and Wee (2004), Odoki et al. (2001), Geurs and Eck (2001), (Burns, 1979), and Pirie (1979)

As described in **Chapter 1**, this research focuses on the transportation component, which constitutes a combination of infrastructure and services that support people in reaching their valuable location(s). Geurs and Eck (2001) described this transport component as the disutility for an individual to overcome the distance between the origin and destination using a specific mode of transportation. They expressed disutility through travel time, cost, and effort to overcome the distance between locations. In practice, the transport components may differ depending on the accessibility approach. However, it is often indicated by the condition of road assets and aspects of transport performance like reliability, comfort and safety.

In this research, accessibility is measured based on constraints to road infrastructure. A reasonable level of accessibility can be achieved when the network is always in service (open to traffic) with acceptable levels of performance. It indicates that the condition of roads should be well maintained to provide reliable access for users regardless of the spatial difference or land-use between regions. Following Hagerstrand's time-space geography theory, a high density of well-maintained roads within an area provides better opportunities for users to engage in social-economic activities (see **Figure 2.1**).



a. Before accessbility improvement b. After accessbility improvement

Figure 2.1 The benefit of accessibility improvement for better opportunities and travel freedom (modified from Odoki et al., 2001; Junoasmono, 2004)

For example, as illustrated in **Figure 2.1a**, an individual has the constraint of working at location k at a specific hour $(t_3 - t_2)$. However, the person also has to be at their neighbour`s home to partake in social activities between t_4 and t_1. Assuming the available transportation allows travel at speed v km/h, then the working time and location (time-space) limits the freedom to do extra activities, which are represented by the shaded prism called 'time-space autonomy'. Based on the prism, there is no chance for a person to engage in activities unless there are improvements to accessibility, such as increased travel speed due to improvements in the condition of roads. It is noticed that improvements in speed increase travel options and freedom by enlarging the time-space autonomy area (see **Figure 2.1b**). Nevertheless, it is also acknowledged that improving speed is not always a viable solution because in some cases, it must be restricted for safety reasons. If not, there will be more accidents, which could result in higher costs to road users and authorities than the perceived accessibility-benefit.

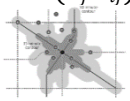
2.2.3 Accessibility Measurement

Measuring accessibility is a challenging task as the term "ease" is determined by an individual`s perception. Each measurement may result in different value and interpretation because it has a specific goal and point of view (Litman, 2016). To date, in the development of the concept of accessibility, the main classification still follows Ingram's theory which separates it into "relative accessibility" and "integral accessibility". The relative accessibility describes the degree of connection between two points. In contrast, integral accessibility describes the extent of access from a given point to all possible points or locations within the study area (Ingram, 1971). This distinction of accessibility supports the grand theory of accessibility defined by Hansen (1959) as "the potential of opportunities for interaction".

The accessibility measurement may be presented either in a mathematical index or score and pictorial indices, and the perspectives are determined by infrastructure, location, personal

constraint, and utility (or perceived benefit) from accessibility. The typical classification of accessibility measurement and points of view are shown in **Table 2.2**, and a further description can be seen in **Appendix A**.

Table 2.2 Various types of accessibility measurement and point of view

Measurement Base	Differentiate	Description or example
Presentation method *(Cohen and Basner, 1972)*	a. Mathematical indices - accessibility index b. Pictorial technique - graphs and isochronal maps	Index: $A_{ij} = \mathrm{f}\left(a_j, t_{ij}\right)$ Pictorial 
Connectivity relationship *(Neft, 1966; Ingram, 1971)*	a. Relative accessibility: between two places (or points) b. Integral accessibility: interconnection a place (or point) with all other places (or points)	Relative: $\overline{a_{xy}} = \frac{a_{xy}+b_{yx}}{2}$ Integral: $A_i = \sum_{j=1}^{n} a_{ij}$
Perspectives or point of view *(Pirie, 1979; Geurs and Eck, 2001; Odoki et al., 2001)*	a. Infrastructure-based: performance or service level b. Location-based: spatially distributed activities c. Person-based: travel constraint d. Utility-based: benefits derived from access to distributed activity	a. Road density, level of congestion, average travel speed on the road network b. number of jobs within 30 minutes travel time from origin locations c. number of possible activities in which an individual can participate at a given time d. the economic and financial benefit

2.2.4 Accessibility in Developing Countries

2.2.4.1 Best practices of accessibility model

In developing countries, the latest best practices of accessibility index application to support regional development are the Integrated Rural Accessibility Planning (IRAP), Rural Access Index (RAI) and Accessibility/Remoteness Index of Australia (ARIA). The IRAP, developed by International Labour Organization (ILO), uses a scoring mechanism with a subjective weighting factor for different indicator values for access to basic needs and services (Dingen, 2000; Dissel, 2003). Meanwhile, the RAI, developed by the World Bank, is concerned more with the physical isolation of locations, and accessibility is measured as "the percentage of the population who live less than 2 km from an all-weather road". This measure aims to ensure that rural populations have adequate access to the transport system (Roberts et al., 2006). Overall,

the ARIA is more appealing than the IRAP because it uses quantitative approaches that minimise any political interference. The ARIA calculates the remoteness of an area by examining the ease at which people can reach service centres based on road distance (Department of Health Australia, 2011). However, one drawback is that ARIA only measures travel time or distance from the centre of a region like a post office, which is the base location (km zero), to reach different service centres. It does not consider the pattern and distribution of roads or the inhabitants in the area. As a result, this measurement usually suggests road authorities focus on arterial road improvement for improving high-speed inter-urban access, rather than considering the lower hierarchy of roads, e.g., collector and local roads. Further information about the technical aspects from the current best practice of accessibility models is presented in **Appendix A**.

2.2.4.2 Accessibility measurement in Indonesia

The implementation of an accessibility model may vary depending on the local characteristics and needs. In Indonesia, the Ministry of Public Works and Housing, which manages the road network, uses road density (km length of road per square km of area) to measure accessibility (Indii, 2016). Based on the measurement perspectives, the model can be categorised as an infrastructure-based accessibility model. The concept of road density developed by the World Bank is clear and straightforward. The measurement encourages road authorities to provide sufficient road infrastructure to support the activities of regional inhabitants. However, road density only measures the availability of road without considering the condition even though it has a significant influence on the performance of aspects of the road network like riding comfort and travel time to reach a destination (Robertson, 2010).

Other agencies, such as the Indonesian Ministry of Health, public services (schools, markets) and agents of commercial property, use ‘travel time to reach a specific destination’ to measure

the level of accessibility (Dimyati et al., 1996; Taki and Lubis, 2017). For example, a house is considered to have excellent accessibility if it takes five minutes to reach a school on foot and two minutes to a market. However, as the origin-destinations are varied, this measurement may only be valid for specific origins-destinations and specific purposes of travel. It would be more meaningful if the measurement took into account the location of essential services as standard destinations. This approach is similar to accessibility measurement in the UK performed by the Department of Transport which measures accessibility by the time it takes to reach seven destinations, i.e., employment, primary school, secondary school, further education, general practitioner (GP) or medical clinic, hospital, food store, and town centre (UK DfT, 2006). Nevertheless, in application, this measurement is still more sensitive to land-use separation and the number of available services rather than toward road infrastructure management itself. Therefore, it is necessary to develop a new accessibility model which focuses on road asset infrastructure features so that it may be linked with the current road asset management regime.

2.3 Climate Change and Extreme Weather Events (EWEs)

2.3.1 Definition of Climate Change and EWEs

2.3.1.1 Climate change

Climate is a long-term distribution pattern of weather (WMO, 2018), and each region has different characteristics based on geographical location and the difference in the angle of the sun, which varies by latitude from the equator (BMKG, 2018c). In recent decades, climate change has become a global issue that afflicts different regions with a variety of threats, with often severe consequences (IPCC, 1990). According to the IPCC (Intergovernmental Panel on Climate Change), climate change is defined as “any change in the climate pattern over time, whether due to natural variability or as a result of human activity” (Pielke, 2004).

Climate change usually leads to increases in the average air temperature, rainfall, wind speed and sea level (Stephenson, 2008; Koetse and Rietveld, 2009). In cold regions like Northern Europe, the increase in temperature may reduce the costs associated with winter maintenance. However, it will trigger more disasters in tropical countries (Willway et al., 2008). For instance, due to its geographical position, Indonesia has been experiencing the most extreme weather conditions in recorded history. Case et al. (2007) reported that tropical cyclones, extreme rainfall, floods, heatwaves, droughts, forest fires and other natural hazards such as landslides occurred more often and were more severe than the previous instances in Indonesia. Climate change not only threatens biodiversity, environmental quality, and the condition of infrastructure, but it can also cause disaster and human death (Case et al., 2007; Measey, 2010; ITF, 2016).

2.3.1.2 Extreme weather events

Extreme weather refers to severe climatic conditions (Markolf et al., 2019). Although the occurrence of extreme weather events (EWEs) is rare with a probability of 0.01 in a particular year (Stephenson, 2008), it has become an issue in transportation infrastructure management due to its catastrophic impact (see **Chapter 2.3.2**). Based on the IPCC terminology, extreme weather events (EWEs) are defined as "individual local weather variables exceeding critical levels on a continuous scale" (IPCC, 2001). It is essentially a weather event that exceeds the upper/lower threshold of local weather patterns within a period (WMO, 2018). However, since climate varies regionally, the definition of extreme weather and its threshold differs from location to location. In practice, based on the statistical approach, extremely high may be interpreted as a value above the 90th percentile and extremely low as a value below the 10th percentile from the historical data pattern (Pezza et al., 2012). Thus, to develop adaptation standards and strategies, it is necessary first to define the extreme threshold and estimate the

probability scenario of its occurrence based on historical climate patterns. Based on the historical data, the threshold of extreme weather parameters in Indonesia is shown in **Table 2.3**.

Table 2.3 The threshold of extreme weather parameters in Indonesia

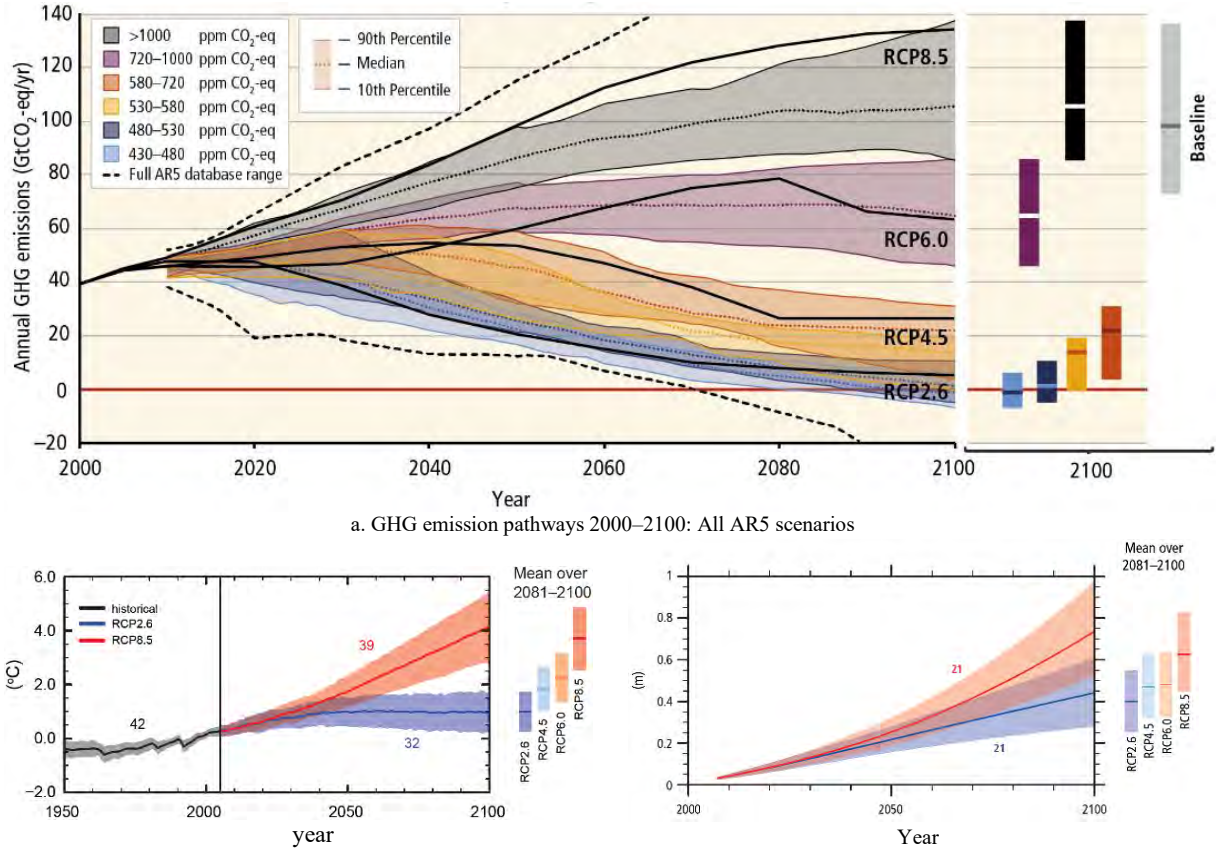
Parameter extreme weather		Extreme threshold	unit
Rainfall (precipitation)		> 100	mm/day
Temperature	Maximum (T_x)	> 37	°C
	Minimum (T_n)	< 15	°C
	Average (T_{av})	> 30	°C
Average humidity (RH)		< 40	%
Maximum wind speed (W_x)		> 20	knot

Source: BMKG (2018a)

2.3.2 Climate Projection and Scenario

Climate is a long-term distribution pattern of weather conditions (Aldrian and Sosaidi, 2013). Each region has different weather characteristics based on geographical location and sun's angle, which varies by latitude from the equator (BMKG, 2018c). The climatic characteristics of a specific location can be observed through its statistical values such as minimum, mean, maximum, or another anomaly condition. Based on historical weather data and greenhouse gas (GHG) estimation, the future climate conditions can be projected using several climate projections models from the IPCC (Bernstein et al., 2007). However, since each climate model has specific parameters, scenarios, and approaches for estimating future climate conditions, the projection outcomes may vary (BMKG, 2010).

In term of greenhouse gas estimation, the GHG projections vary depending on national climate policy and socio-economic development indicators like population, land use patterns, energy use, lifestyle, and technology (IPCC, 2014b). In the IPCC fifth assessment report (AR5), the IPPC accommodate these variances by offering some projection scenarios associated with the likelihood of GHG concentration pathways (see **Figure 2.2**). The scenario of the Representative Concentration Pathways (RCPs) consists of low GHG emissions (RCP 2.6), intermediate GHG emissions (RCP 4.5 and RCP 6.0) and high GHG emissions (RCP 8.5).



a. GHG emission pathways 2000–2100: All AR5 scenarios

b. Global projection of surface temperature (relative to 1986–2005)

c. Global mean sea level projection (relative to 1986–2005)

Scenario: RCP 2.6 (low GHG emissions); RCP 4.5 and RCP 6.0 (intermediate GHG emissions); RCP 8.5 (high GHG emissions)

Figure 2.2 Climate change impact on global temperature and mean sea level (after IPCC, 2014a)

As illustrated in **Figure 2.2**, the outcomes of climate prediction varied following the RCP scenario. The more pessimistic that the GHG concentration can be controlled, e.g. RCP8.5, the higher increase in climate parameters generated, e.g. temperature and mean sea level. Although the GHG scenario is predefined, the projection outcomes may still indicate wide variation as each model has different variables and approaches (IPCC, 2007). Thus, the projection should not just rely on one climate model, but instead, compare outcomes from several models and make a proper resume based on it (ADB, 2015; Elliott, 2016). In the aggregation procedure, Porfirio et al. (2014) warned that important information might be lost if the values are inappropriately summarised. Through his research into improving the use of species

distribution models under climate change, he demonstrated that the use of the median value to aggregate several IPCC climate-models is more appropriate than the value itself. He found that resuming multi-model outputs using the 'mean' value does not consider the variability of parameters and approaches represented by the different climate model and emissions scenarios. Accordingly, the median value from five IPCC climate-models was used in this research (i.e. BCC-CCSM1-1, GISS-E2-R, IPSL, MIROC5, and HadGEM2-ES) with the focus placed on the maximum, minimum and intermediate climate projection patterns (see **Figure 2.3**)

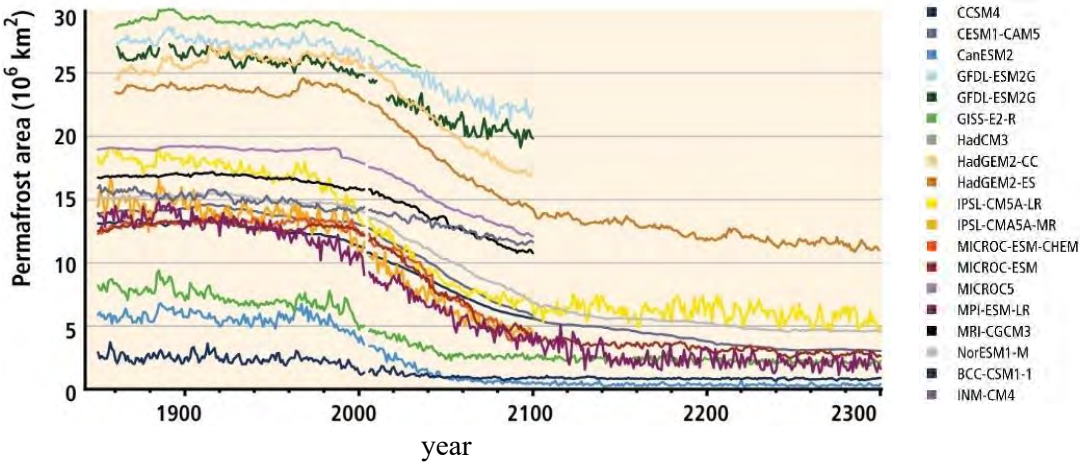


Figure 2.3 The multi-models of IPCC climate projection for simulating the extent of permafrost in the Northern Hemisphere (after Settele et al., 2015)

2.3.3 Climate Impact on Road Networks Infrastructure

In recent decades, road infrastructure has been exposed to extreme weather events (EWEs) which cause problems in the provision of transportation, and to the infrastructure. In general, extreme events are complex. However, they can be characterised based on frequency, severity, and duration (Stephenson, 2008). The weather threats are typically triggered by meteorological characteristics such as heavy precipitation, extremes of temperature, high wind speeds (e.g., cyclones, typhoons), and a higher natural hazard risk. Due to global warming, these extreme weather events are happening more frequently and with increased severity (Schweikert et al.,

2014a). In the transportation sector, this condition is a significant issue because disruption to the performance of the road network can harm transport services, people, and businesses in numerous ways. For instance, extreme rainfall causes flooding to subways and roads, and it can also trigger landslides and cause bridges to collapse (see **Figure 2.4**).



(a) flood (b) Strong wind speed

(c) bridge fail, river flood (d) landslide

Source: a,b After UK DfT (2014); c, d After CCAP and EESI (2011)

Figure 2.4 The potential impacts of extreme weather events (EWEs) on accessibility

In term of road pavement, previous work on climate change showed that in the long term, climate might affect the condition of pavement (IPCC, 2007). EWEs cause severe damage and shorten pavement life (Schweikert et al., 2014b; Qiao, 2015). Road pavement infrastructures are usually designed based on historical local climatic patterns. The design standards take into account the variability in temperatures and precipitation levels as a safety factor (Alam and

Zakaria, 2002; Bina Marga, 2017). However, it is often insufficient to withstand the uncertainty associated with climate change. During the design life, a pavement could be tested under different climatic conditions, including extreme weather events (OECD, 2015b). The designs standard and maintenance of roads should be adapted by considering such conditions and the potential impact on the performance of road networks. The illustration of the potential impact of climate change and extreme weather on the condition of road assets and accessibility in tropical countries are presented in **Table 2.4**.

Table 2.4 The potential impact of climate change and extreme weather on the condition of road assets and accessibility in tropical countries

Climate change variable [a]	Extreme weather	The potential impact on transportation	
		Road asset	Accessibility
Increase in temperature	▪ Heatwaves ▪ Drought	▪ Deterioration of material: Rutting, bleeding, asphalt ageing (thermal fatigue) ▪ Dried trees and vegetation ▪ pavement deformation: buckled and expansion	▪ speed reduction due to worsen pavement condition ▪ Reduced travel comfort for pedestrian, bicycle, motorcycle ▪ Delays: increased travel time due to partial cut or roadblock ▪ Loss of connection due to roadblock/damage
Increase in rainfall (precipitation)	▪ Extreme rainfall ▪ Flood ▪ Landslide	▪ slope failure and landslides (Soil expansion, erosion, loss-bearing capacity) ▪ Embankment scouring of damage surface pavement ▪ Reduced sight distance ▪ Reduced skid-resistance due to hydroplaning	▪ congestion ▪ delays: reduced speed or partial roadblock ▪ accidents: lower skid resistance and reduced sight distance due to heavy rain ▪ loss of connection due to roadblock
Increase in wind speed	▪ Storm/ Cyclone ▪ Storm surge ▪ Strong wind	▪ Physical damage to road furniture: road sign fall, Trees fall	▪ Increased travel time due to partial cut or roadblock ▪ Loss of connection due to roadblock/damage ▪ Cancelled trips
Sea level rise	▪ Flood ▪ Abrasion ▪ Seawater intrusion ▪ Groundwater level	▪ Substructure scoring ▪ flood ▪ Corrosion from saltwater, ▪ Soil saturation (loss of bearing capacity)	▪ Increased travel time due to partial cut/roadblock (flood) ▪ Loss of connection due to roadblock/damage

a. incremental change in the intensity, frequency, or duration
Source: Rowan et al. (2013); ADB (2014) , Suriadi et al. (2013), Mehrotra et al. (2011), Willway et al. (2008), Humphrey (2008)

Based on **Table 2.4**, it is noticeable that climate change and extreme weather mostly harm road assets and accessibility in tropical countries. The impact of EWEs is often severe because it not

only decreases accessibility through delays or degraded road conditions, but they can also cut road connections completely following landslides or flood damage to bridges (see **Figure 2.4**). Accessibility refers to the ease at which people can reach their desired destinations. Failure to maintain road network accessibility restricts social-economic activities and results in higher levels of poverty. This situation has forced road authorities to perform more frequent maintenance which requires a higher maintenance budget (Meyer et al., 2013; Stamos et al., 2015).

2.4 Summary

Different accessibility measures can yield varying results which is the main challenge while using accessibility as a performance measure. To develop an appropriate accessibility model, it is essential to first define the aims and definition by considering the intended end-users and the field of application, especially when selecting the measurement technique. The measurement not only needs to satisfy the theoretical base of accessibility but should also reflect the real condition. A higher level of accessibility offers more opportunities and options for road users and local inhabitants to travel and to reach locations in less time and at a lower cost.

Climate effects are subject to uncertainty, but the uncertainty can be managed using climate models and likelihood scenarios of GHG concentration pathways. However, due to modelling limitations, the full effects of extreme weather are still mostly unknown. EWEs have forced road authorities into performing more frequent road maintenance, which requires higher budgets. As a consequence, it is necessary to reserve an emergency budget to react adequately to the occurrence of extreme weather events.

CHAPTER 3

METHODOLOGY

3.1 Introduction

This research aims to find out how road network accessibility should be managed to cope with climate change and extreme weather conditions. Therefore, it is necessary to develop a model capable of linking accessibility with lifecycle analysis and climate change. This model seeks to produce an accessibility criterion within a road asset management procedure to promote regional development. Although several accessibility models examine the accessibility of road networks (Geurs and Wee, 2004; El-Geneidy et al., 2011), most do not explicitly take into account the condition of the road infrastructure and its lifecycle. To address this gap, an enhanced accessibility model coupled with a life cycle analysis of road assets may provide sustainable standards and strategies that allow for an optimum level of accessibility.

This methodology chapter explains how the research was carried out and contains seven sections. Immediately after this introduction, the second section presents the concepts and approaches used to develop an accessibility model and shows how this model may be implemented innovatively to manage road network infrastructure in changing climatic conditions. This approach is elaborated on in the following sections.

3.2 Overall Approach

An appropriate road network management system should provide, at the minimum, a reasonable level of accessibility to locations in need of transport services (Amrozi and Evdorides, 2019). However, concerning the new management of road assets, two issues have arisen. First, the decision criteria for roadworks and budget allocation is mainly focused on economic

assessments, with less focus on accessibility. Thus, the assessment assigns more weight to the 'scale of the traffic'. As a result, in terms of budget allocation, road assets in remote areas typically have a lower priority over assets in more accessible areas with more traffic and inhabitants. Accordingly, the accessibility level in remote areas decreases or remains low, and the disparity across regions increases. Second, extreme conditions attributable to climate change speed up pavement deterioration and cause damage to road infrastructure. These conditions may trigger more frequent roadworks, which results in a higher budgetary requirement (see **Chapter 2**). Since worsening road conditions reduce accessibility levels, the road management and accessibility model should consider this. To address these two issues, in addition to economic assessments, accessibility needs to be included as a criterion to improve current road management standards and strategies aimed at optimising the condition of road networks to support regional development under tight budgetary constraints. The road asset management frameworks to accommodate accessibility and climate change are illustrated in **Figure 3.1**.

Adding an accessibility criterion in road network management is theoretically simple. However, it leads to various interpretations in practice due to the prevalence of different types of accessibility measures and perspectives. Several models can be used to measure accessibility (see **Chapter 2.2**). However, the application of these accessibility measures can lead to erroneous results because:

1. Existing accessibility measures do not explicitly take into account the condition of the road infrastructure and its economic life.
2. Existing accessibility measures give more concern to land use than transportation components.

3. There is no link to accommodate environmental issues such as climate change or extreme weather conditions to the level of accessibility.

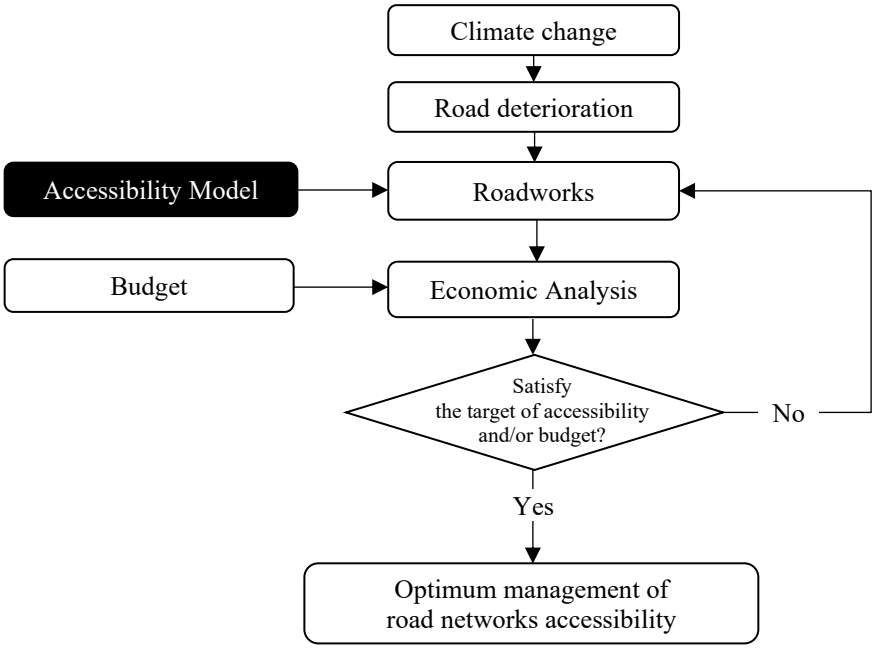


Figure 3.1 Inclusion of accessibility criterion to manage road networks accessibility

To address these gap, the development of an accessibility model should focus on the transportation component by directly including road infrastructure and its condition because these components are susceptible to climate change parameters and the level of accessibility (see **Figure 3.2**).

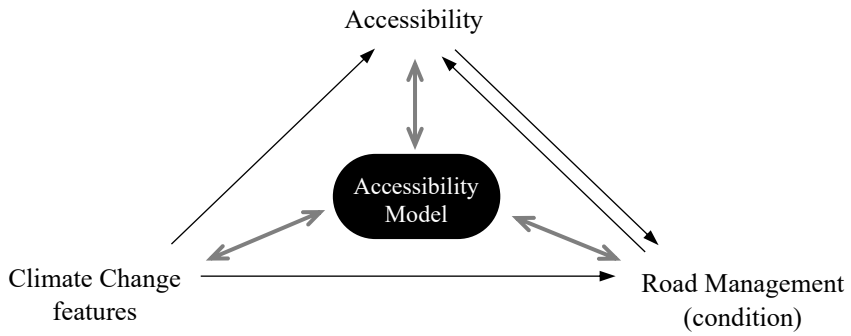


Figure 3.2 Accessibility model to link accessibility with road management and climate

Overall, developing an accessibility model is the most critical part of this research. Accessibility is used as a measurement tool to promote regional development. The inclusion of accessibility criteria, along with economic analysis in road asset management, becomes the fundamental approach to address both climate change and the problem of accessibility. In this research, the implementation of the accessibility model has two essenztial objectives:

1. To ensure equity or fairness both in the quality and distribution of accessibility for each person in the country. The concept of equity is chosen to maintain the accessibility level and minimise the disparity between locations to promote regional development.
2. To achieve sustainable road network accessibility, i.e. optimising the condition of road network assets to achieve an optimum level of accessibility under tight budget constraints and changing climate conditions.

The accessibility model needs to be tested using real data to ensure that the developed accessibility model is practical. The data includes road asset characteristics, maintenance standards and climate change attributes. Located in a tropical climate area and with a GDP of 3,491 USD per capita in 2014 (World Bank and OECD, 2017), Indonesia is comparable with other developing countries with a tropical climate and low to medium-income levels (see **Figure 3.3**). Although the overall approach in this research is tested using data from Indonesia, the models can be applied in other countries or areas. A further description of Indonesia as a case study, including its data characteristics, are presented in **Chapter 4** and **Appendix B**.

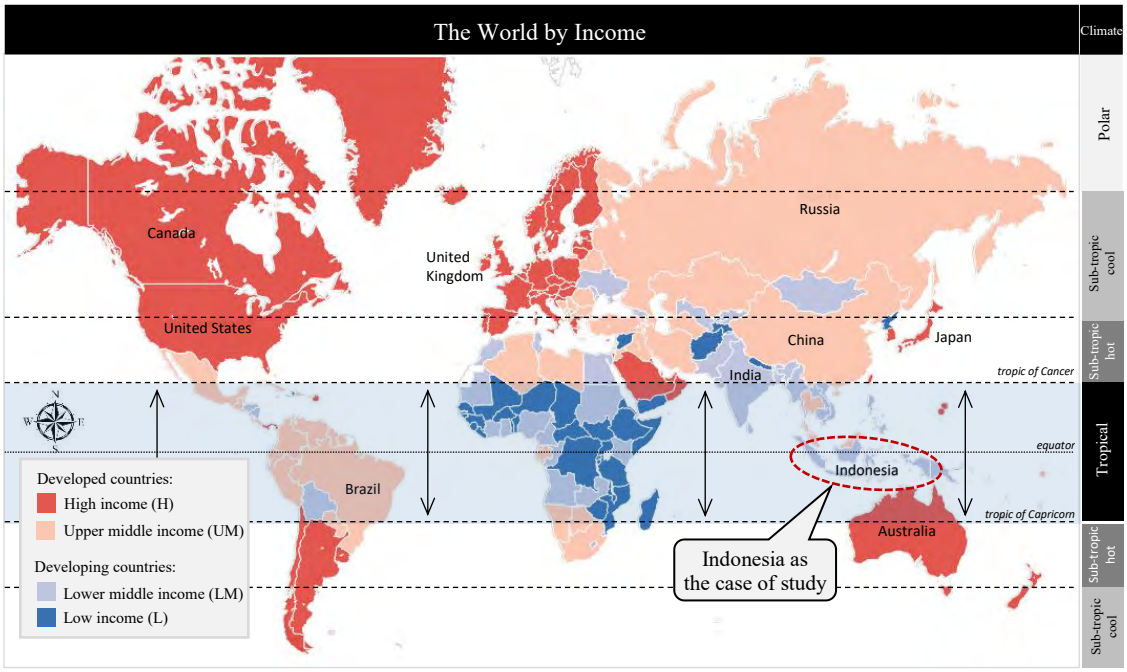


Figure 3.3 The world by the income year 2014 (based on World Bank database, 2019)

3.3 Supporting Regional Development through Infrastructure-based Accessibility

Investment in road infrastructures is a key component to support regional development, especially in less prosperous locations. There is ample evidence to suggest a positive relationship between transport infrastructure investment and regional development (Caschili et al., 2015). Aschauer (1990) and Rephann (1993) evaluated statistical evidence showing the positive effect of transport infrastructure on macroeconomic measures such as gross domestic product (GDP). In the area of microeconomics, Medda (2012) and Xiao et al. (2016) pointed out that investment in transport infrastructure increases the attractiveness of commercial and residential real estate properties because of improved accessibility levels. According to the transport land-use feedback cycle theory, as seen in **Figure 3.4**, investing in road infrastructure provides multiple benefits to local inhabitants and supports regional development. Therefore, in this research, the approach for accessibility improvement focuses on road network infrastructure and its condition.

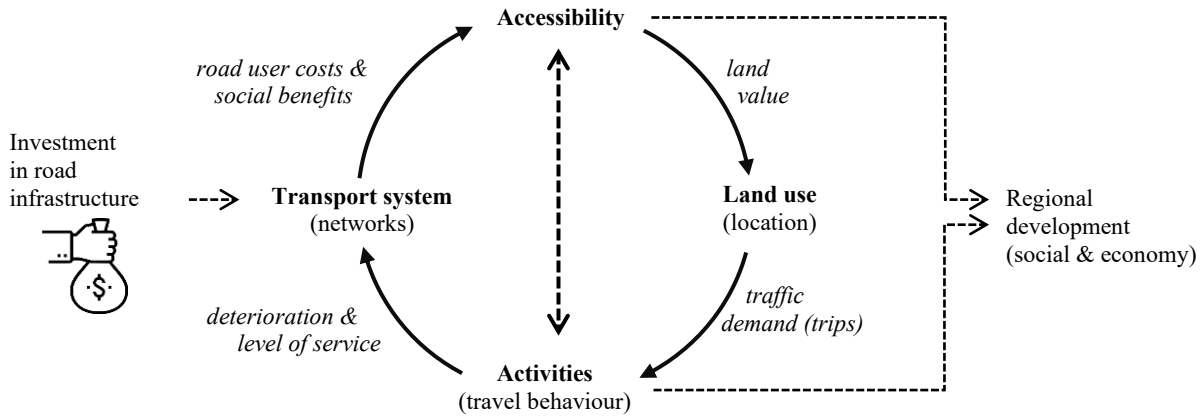
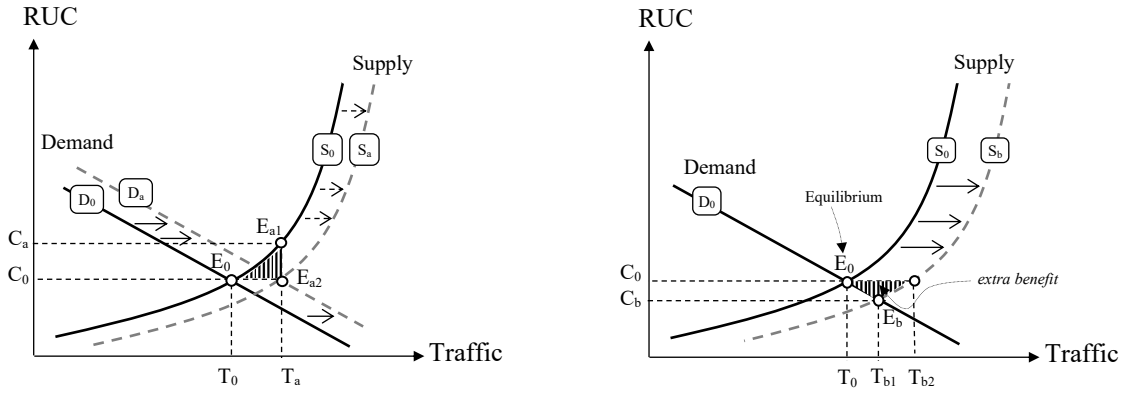


Figure 3.4 Intervention of road infrastructure investment on transport land-use feedback cycle (adapted from Wegener and Fürst, 1999; Bertolini, 2012)

Investment is defined as the total amount of money spent to preserve and develop road network infrastructure, including recurrent and capital budget (Banister and Berechman, 2003). There are two investment approaches in road transportation, i.e. investment that follows traffic and investment to generate traffic (Button, 2010). The first approach, an investment that follows traffic or transport demand, is a passive approach intended to preserve the condition of road networks at an appropriate level. As illustrated in **Figure 3.5a**, the increasing demand for travel (D_0 to D_a) which is reflected by an increasing number of traffic (T_0 to T_a), increases the road user cost (RUC) from C_0 to C_a. Higher traffic flow may accelerate road deterioration (due to extra loads) and increase congestion (due to insufficient road capacity). Through using economic assessments in road asset management, these circumstances force road managers to repair, widen, or improve existing infrastructure (supply) to meet the road performance standard or minimum level of service (S_0 to S_a).

The second approach, investment to generate traffic, is a proactive action to improve road network performance. The invested budget is intended to provide extra supply (S_0 to S_b), e.g. to improve the accessibility of different locations, reduce travel costs, and improve location attractiveness, i.e. from C_0 to C_b (see **Figure 3.5b**). These extra benefits attract more people to

engage in social-economic interactions and activities that result in increased traffic flow (T_{b2}-T_0).



(a) Investment follows traffic (b) Investment to generate traffic

Figure 3.5 Investment approach in road infrastructure

As this research investigates strategies to promote regional development in a developing country, the second investment approach appears more relevant to the context of road network accessibility management. It means that the inclusion of accessibility as an additional criterion in road asset management may balance the weight between accessibility management and economic appraisal, which was previously dictated by traffic flow. As a result, the overall investment approach is theoretically improved.

3.4 Development of Accessibility Model

3.4.1 Definition of Accessibility

Accessibility in this research is defined as 'the extent to which road network infrastructure ease road users to reach their destination(s) throughout the year within a particular region' (Amrozi and Evdorides, 2019). The associated model emphasises how road infrastructure may be optimised to maintain accessibility and support regional development under changing climate conditions using the concept of equity.

3.4.2 The Concept of Equity in Accessibility Model

Equity is a fundamental concept to achieve sustainable development (Banister and Berechman, 2003). It implies the need for fairness both in the distribution of benefits or losses and the entitlement to a quality standard of living (Beder, 1996). As pointed out by Hay and Trinder (1991), most transport policymakers believe that the concept of equity must at least cover the principles of formal equality (equal treatment within a reference group) and basic needs (minimum requirements to fulfil particular universal objectives). This concept ensures that people are treated as equals in the sense that no one suffers a burden or enjoys a benefit disproportionately while securing a minimum level of accessibility (see **Figure 3.6**).

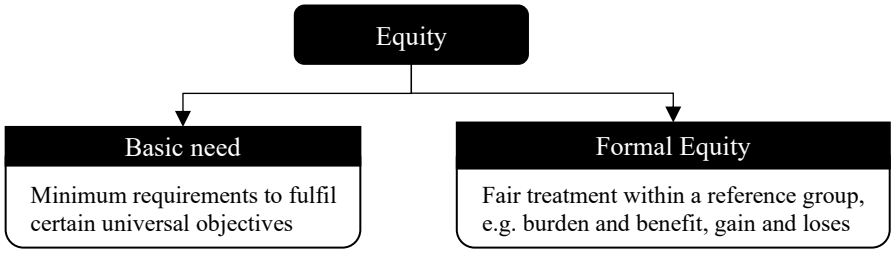


Figure 3.6 The concept of equity in road infrastructure

In this research, the concept of equity concerns fairness regarding access. Foremost, road networks should be managed to provide necessary access for inhabitants in need of transport services. Once it is satisfied, the next urgency is to maintain a fair distribution of accessibility levels through the development of appropriate strategies. In practice, the physical road infrastructure may not be equal, but as a system, the road network should offer equal access to provide the same benefits or opportunities.

3.4.3 Accessibility to Link Communication Between Stakeholders

The concept of accessibility has been widely used in transport and land-use planning. Accessibility models are intended to link and ease communication between road authorities and other stakeholders (e.g. road users, road board members, governments) in managing road

networks (see **Figure 3.7**). Since each stakeholder may have a different background of knowledge and interests, the accessibility model should be simple and easy to interpret. For example, engineers or road managers can use the accessibility model with an engineering-based index associated with road infrastructure features such as road density or roughness. This approach makes the index more applicable because it is easier for road managers to synchronise with existing road asset management tools like the HDM-4. However, the term for accessibility components should be simple or less technical, and the final index can be converted or associated with a popular indicator such as a star rating system which makes it easier for politicians, road users and ordinary people to understand. Furthermore, to anticipate political interference, the accessibility measurement needs to be more quantitative than qualitative.

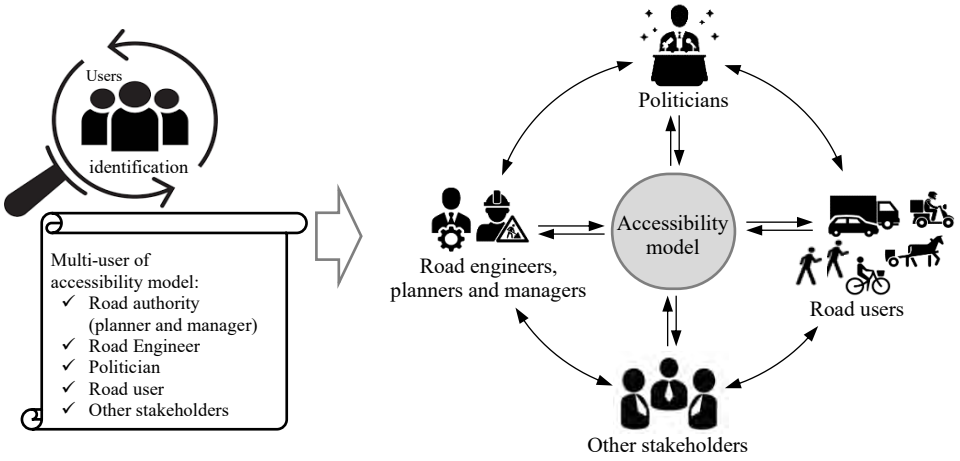


Figure 3.7 Accessibility model to link communication between stakeholders

3.4.4 Method for Developing Accessibility Model

Building an accessibility model is an essential part of this research. Based on the measurement perspective (see **Chapter 2**), the accessibility model developed in this research is categorised as an infrastructure-based accessibility index. This model is designated to integrate the concept of accessibility with climate change and road asset management attributes (see **Figure 3.8**).

Thus, road network infrastructure and its condition become the predominant factors affecting the level of accessibility.

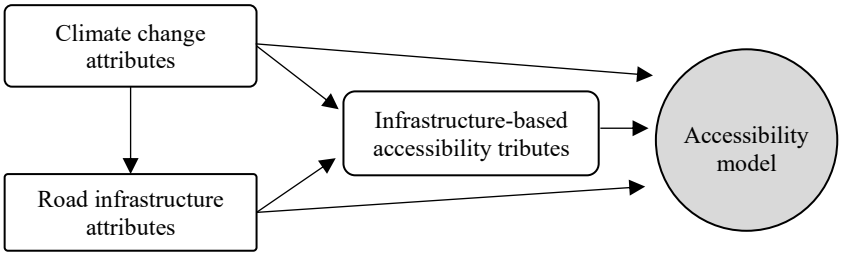


Figure 3.8 Attributes contributing to accessibility model

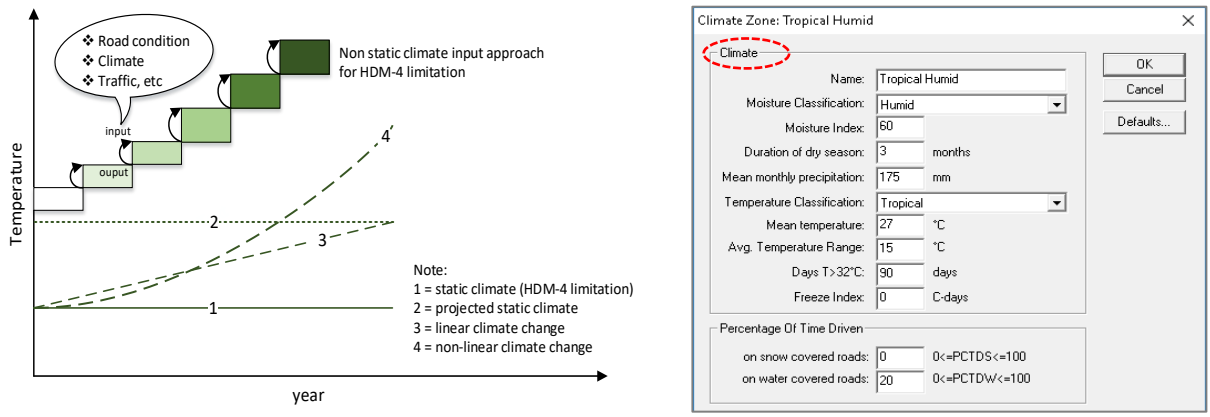
The infrastructure-based accessibility model was developed using composite indicators and a statistical analysis technique following the "Handbook on Constructing Composite Indicators", which was developed by the Organisation for Economic Co-operation and Development (OECD). This method is selected due to the complex features of accessibility, which is multi-dimensioned but can be quantified and aggregated into a single index. The technical procedures to build a model using the composite indicator's method can be seen in **Chapter 5**.

3.5 Climate Change Adaptation

The options to mitigate the adverse effects of extreme weather events (EWEs) on transport infrastructures are broadly be divided into control and adaptation (Rattanachot et al., 2015). Control is a proactive approach to reduce the underlying factors that contribute to climate change, such as a reduction of greenhouse gases (GHG) emissions. Meanwhile, adaptation is a passive approach with the purpose not being to influence the climate, even though it may unintentionally do so, but to find ways to reduce the vulnerability of transport infrastructure in a changing climate. As the scope of this research is road network management, the EWE mitigation approach focuses on adaptation.

In practice, adaptation strategies are broadly divided into three categories: (1) abandon by 'do minimum' or 'do nothing,' (2) maintain and manage, (3) strengthen and protect the existing infrastructure (De Bruin et al., 2009; Auerbach et al., 2016). Each adaption option may have different maintenance standards and strategies. Therefore, to find out the optimum adaptation standards and strategies, the three options need to be assessed using the lifecycle-cost analysis software HDM.4 which is a standard decision support tool used in road asset management in Indonesia (Morosiuk et al., 1999). In this study, using the HDM-4 as a decision support tool was the most appropriate and practical.

As a decision support tool, the HDM-4 has a limitation in modelling the impact of the climate on road conditions. Although it can model specific climate types, it does not seem to cater for climate change phenomena. This limitation may be mitigated through time-series modelling, i.e., setting the output from the previous time-slot assessment as the input for the next time-slot assessment (See **Figure 3.9a**). However, as the road asset management cycle is typically simulated for a ten or twenty-year period and the climate is changeable over longterm periods (decades), the climate input in the HDM-4 is not necessarily adjusted annually. Adjusting the climate parameters following the typical pattern of an analysis period in road asset management, e.g. every five years, could be sufficient (see **Chapter 4.5.2**).



a) adjusting climate change on HDM-4 b) climate input on HDM-4 (Screenshoot from HDM-4 Software)

Figure 3.9 Adjusting climate change inputs on the HDM-4 tool

3.6 The HDM-4 Economic Analysis

Road maintenance has the purpose of reducing pavement deterioration rates (Faiz and Harral, 1988; Robinson, 2008). Proper management ensures that road networks always provide an optimal level of service. As a result, it may reduce vehicle operation costs (RUC), improve road safety and keep the road network continuously open throughout the year. However, to achieve such an optimum condition also requires financial resources. Thus, the proposed maintenance standards and strategies to adapt to climate change and extreme weather conditions should not only satisfy the engineering aspect but also be economically feasible. In road asset management, the economic benefits from the application of maintenance standards and strategies are estimated by comparing the investments made during the corresponding budget period with a base-scenario of investment deferred to the next budget period, as illustrated in **Figure 3.10**.

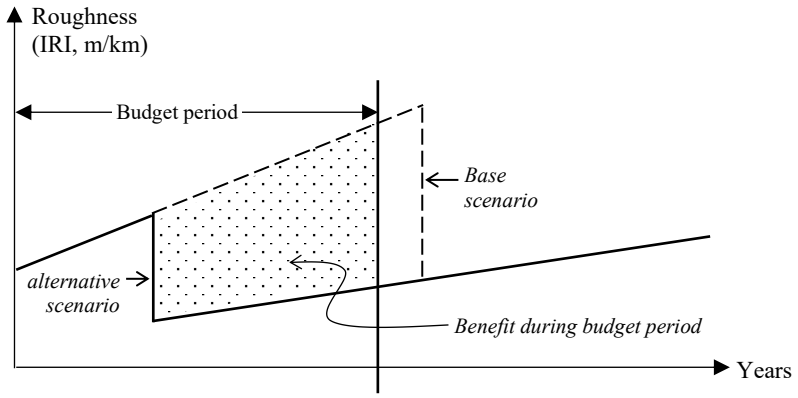


Figure 3.10 Calculation of road project benefits during the budget period (after Kerali et al., 1998)

In this research, road asset management is carried out at a strategic level of analysis. At this level of analysis, the HDM-4 identifies the budget required to achieve an optimum level of accessibility. However, if the budget is constrained, it can help road managers to simulate the optimal road network performance that can be achieved, e.g. the level of accessibility, during the analysis period.

3.7 Summary

This methodology chapter acts as a brief guideline to carrying out this research. It presents the overall concepts and methods for developing an accessibility model and shows how this accessibility model may be implemented innovatively to manage road network infrastructure under changing climate conditions. Although the overall approach is tested using data from Indonesia, the models can be transferred and used in other countries or areas.

The accessibility model was developed using the composite indicators technique and statistical analysis following the "Handbook on Constructing Composite Indicators" from the Organisation for Economic Co-operation and Development (OECD). The model emphasises the concept of equity through road infrastructure features and its condition. Although accessibility is 'not necessarily the same', the distribution should be reasonable nationwide, and there should be minimal disparity between regions.

The inclusion of accessibility criteria, along with an economic analysis within a road asset management procedure (e.g. using the HDM-4) became the primary approach for managing road network accessibility and promoting regional development. In the application, the accessibility model defines sustainable standards and strategies that enable an optimum level of accessibility.

CHAPTER 4

CLIMATE CHANGE IN INDONESIA AND ITS IMPACT ON ROAD CONDITIONS

4.1 Introduction

This chapter describes how climate change and extreme weather conditions can affect the overall condition of road networks in low and middle-income countries, as well as, how they perform when used with HDM-4, the standard decision making support tool in road asset management. The characteristics of Indonesia as a case study are described to provide a representation of the typical characteristics found in developing countries.

This chapter consists of five sections. First, a profile of Indonesia is presented to give a better understanding of the conditions and circumstances in the case study. The following section explores climate parameter inputs in the HDM-4 model to understand how the model behaves with changeable climate parameters, using Indonesia as a case study. Afterwards, some approaches to feed the HDM-4 life cycle cost analysis (LCCA) with climate change parameters are also simulated and evaluated.

4.2 Indonesia as the Case Study for Developing Countries

4.2.1 Country Profile

Indonesia is a tropical country located in Southeast Asia with Jakarta as the Capital city. In terms of population, in 2018, Indonesia was the 4th most populated country with 267.7 million inhabitants (World Bank, 2019). According to BPS-Statistics (2018), most people in Indonesia work in the agricultural sector (29%) followed by trade (23%) and services (16%).

Indonesia is the largest archipelago in the world and is 1.9 million square km in area. It consists of five big islands, and thousands of smaller ones (16,056 islands) spread over 34 provinces (see **Figure 4.1**). The five biggest islands are Sumatera, Java, Kalimantan (Borneo), Sulawesi and Papua. With hundreds of native languages, Indonesia has a diverse cultural background and social fabric. However, there is also a shared language, called Bahasa Indonesia, which helps to foster a strong national identity.

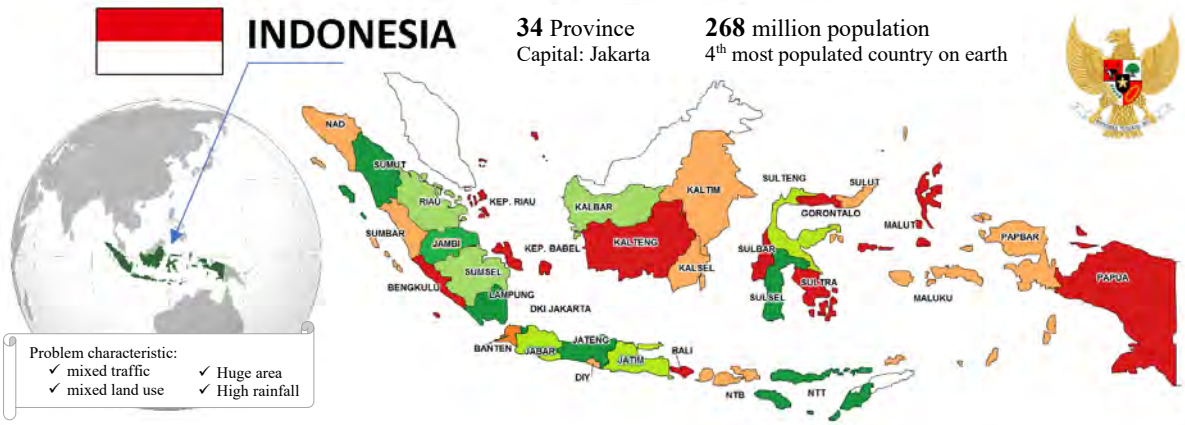
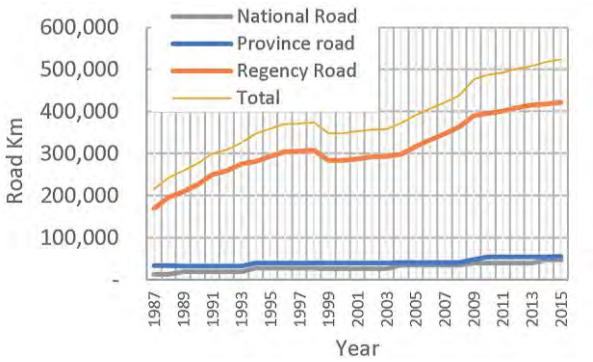
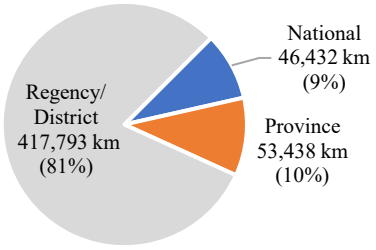


Figure 4.1 The map of Indonesia as a case study

In terms of transportation sector, although Indonesia is the largest archipelago in the world, the primary transportation system is based on roads rather than water (BPS-Statistics, 2018). Indonesia has the most extensive road network in ASEAN (the Association of South-East Asian Nations), and there were 517 thousand km of roads in 2014 (Indonesian Ministry of Public Works, 2016). Overall, the primary roads linking major cities are in good condition and serve as the leading primary-arterial network. However, some provincial and regency/district roads are in poor condition, which limits connectivity between regions, especially in the east of the country during the rainy season (Gultom et al., 2017). The general picture of road asset development in Indonesia and its typical condition are shown in **Figure 4.2** and **Figure 4.3**.

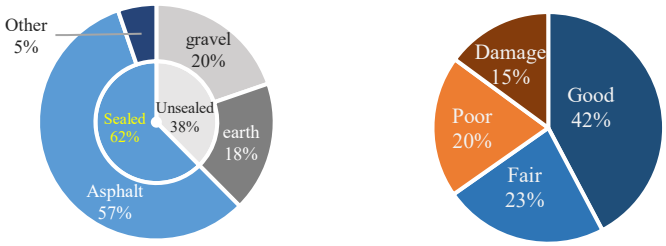


a) Road asset by ownership



Total Assets 517,663 km

b) Distribution of Road assets by ownership (2014)



c) Distribution of road assets by pavement type and condition in the year 2014

Source: Indonesian Ministry of Public Works (2016)

Figure 4.2 Road assets in Indonesia



a) National road b) Provincial road c) Regional road

Note: the picture shows typical road type and condition but not with actual/regular traffic

Source: the picture was captured from www.google.co.uk/maps with road list from Yogyakarta Road Authority.

Figure 4.3 Typical road conditions in Indonesia

4.2.2 Road Asset Management in Indonesia

The authority for roads in Indonesia is shared between two ministries: (1) Ministry of Public Works and Housing which is responsible for infrastructure management aspects like construction, repairs, and development; (2) Ministry of Transportation which is responsible for

traffic management (see **Figure 4.4**). Each ministry has an organisation at different levels of government which reflect the degree of authority held, i.e., national, provincial, and regency (local level). Accordingly, the data and analysis of road asset management in this research should follow the standards and regulations from the Ministry of Public Works and Housing, which is the leading authority on road infrastructure in Indonesia. The typical characteristics of the Indonesian road network based on the function and ownership of assets can be seen in **Figure 4.5** and **Table 4.1**. Further information about Indonesian maintenance standards is contained in **Appendix B**.

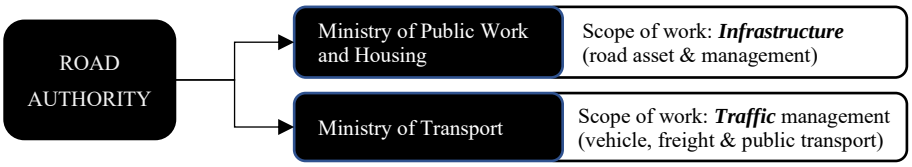


Figure 4.4 Road authority scheme and responsibility in Indonesia

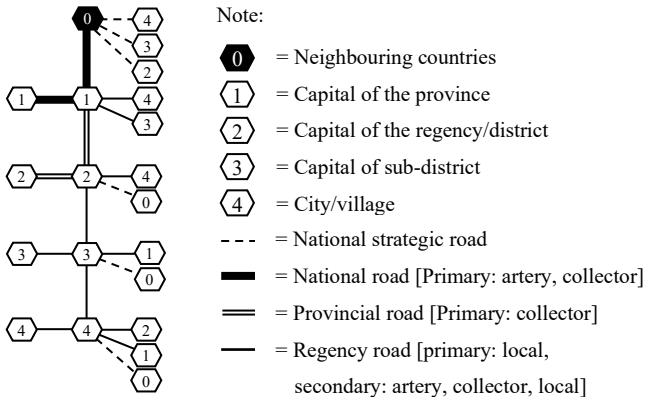


Figure 4.5 Road category based on function in Indonesia

In Indonesia, road assets are managed based on the optimisation results from the Indonesian Integrated Road Management System (IRMS) (Harral et al., 2011). The IRMS system was developed by the Ministry of Public Works of Indonesia. It was based on the conceptual model of the Highway Design and Maintenance Standard series III (HDM-III) from the World Bank (Hutabarat, 1994). Accordingly, the typical data used as the HDM-4 inputs for simulating the

road conditions under changing climatic conditions can be taken and linked to the IRMS database. The data includes road length, pavement type, pavement strength, pavement condition, roadworks costs and maintenance standards. The illustration of the IRMS interface where the road asset data for Indonesia is entered and stored can be seen in **Figure 4.6**.

Table 4.1 Comparison of road category in Indonesia with other countries

Road Network in Indonesia			International		
Status	Owner	Function	USA [b]	UK [c]	Europe [d]
National Road	Central government (Gov. level 0)	▪ primary artery (connect national level service centre) ▪ primary collector-1 (connect between province capital) ▪ national strategic road ▪ toll road	Primary Artery	Motorway, A Roads	National road, European Road
Province Road	Provincial government (Gov. level I)	▪ primary collector-2 (connect between province & regency capital) ▪ primary collector-3 (connect between regency capital) ▪ province strategic road	Primary Collector	B Roads	County road
Regency Road	Regency/district government (Gov. level II)	▪ secondary (arterial, collector, local) ▪ regency strategic road	Local	C Roads	Communal and municipal roads

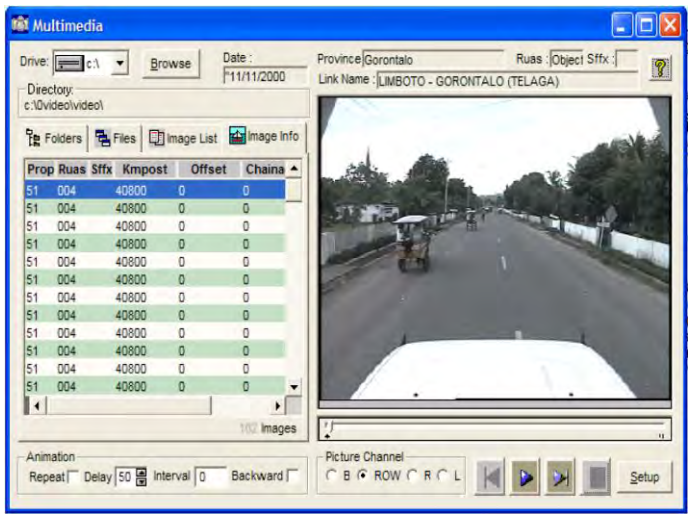


Figure 4.6 User interface of IRMS database

4.2.3 Climate and Weather in Indonesia

Due to its geographical location, Indonesia has a humid tropical climate with only small fluctuations in temperature throughout the year (Gosling et al., 2011). There are two seasons in

the year, dry and rainy. The mean annual temperature is around 26.9 °C, and the average level of precipitation around 132 mm/day over the last decade (see **Figure 4.7**).

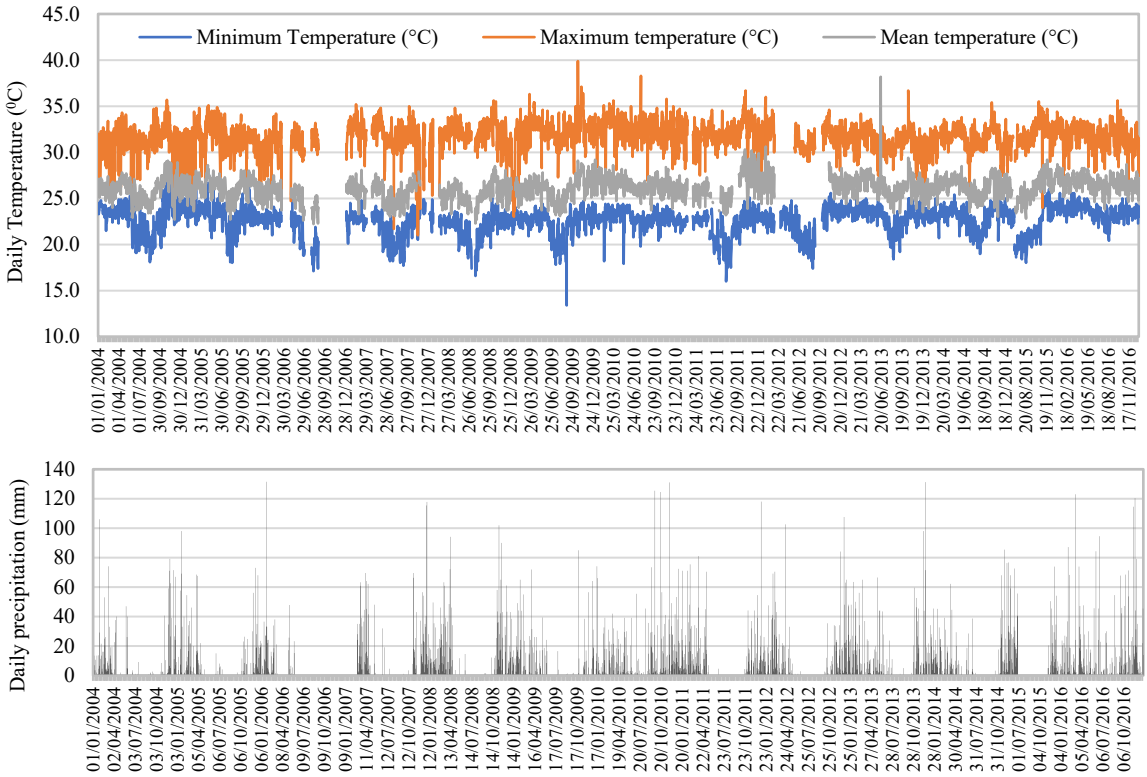


Figure 4.7 Historical weather pattern in Indonesia in the last decade (after BMKG, 2018b)

Because it is situated between two oceans (the Pacific and the Indian) and two continents (Australasia and Asia), Indonesia has varied weather characteristics, including heavy rain and high temperatures (Taufiqqurahman, 2018). Extreme weather such as heavy rainfall and hot temperatures typically occur in the transitional periods between seasons, e.g. in October and March (BMKG, 2017; Yushar and Ariastuti, 2017). During the last decade, the highest temperature anomaly occurred in 2016 (BMKG, 2019). As illustrated in **Figure 4.8**, the mean temperature increased by up to +1.4 °C across Indonesia compared to the previous averages from 1981-2010. It signifies that global warming is happening and may increase the frequency of disasters in Indonesia. Based on historical pattern (see **Figure 4.9**), The Indonesian National Board for Disaster Management (BNPB) predict mainly hydrometeorology events such as

flooding, landslides and forest fires. Thus, the further impacts of climate change on road networks accessibility should be identified and mitigated against.

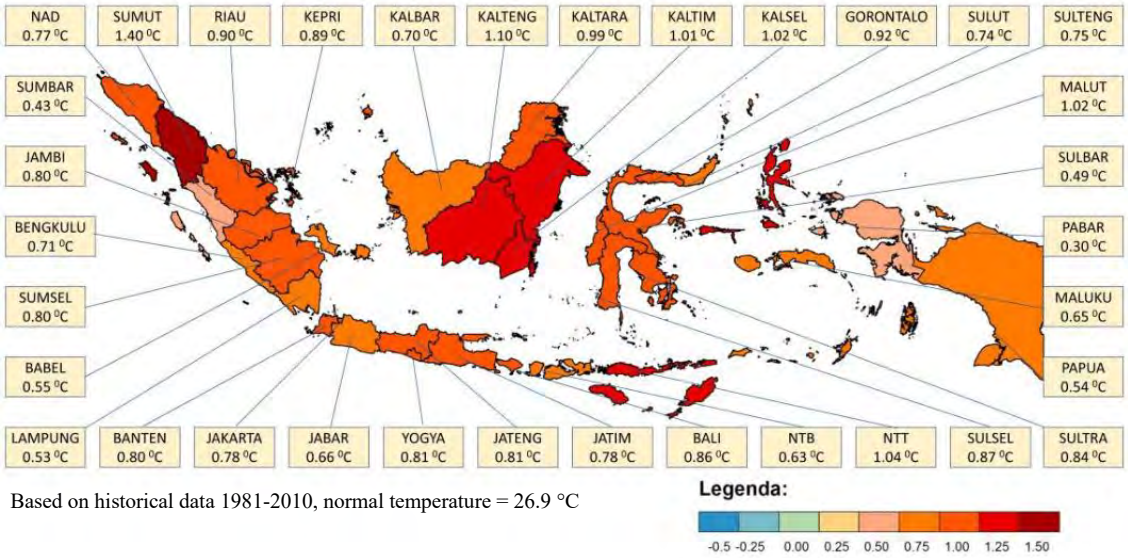
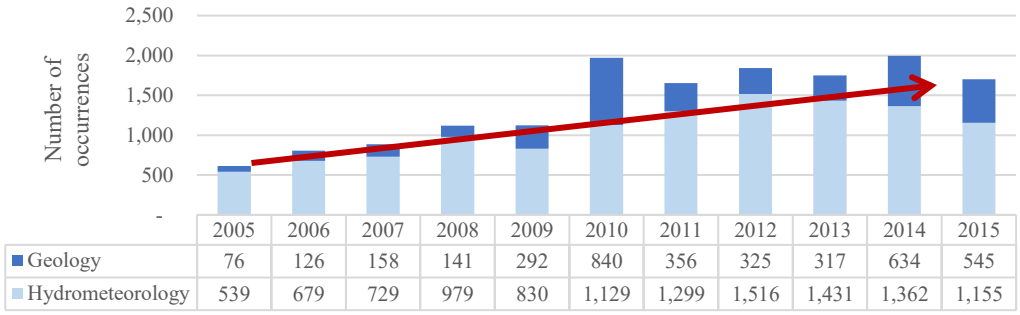
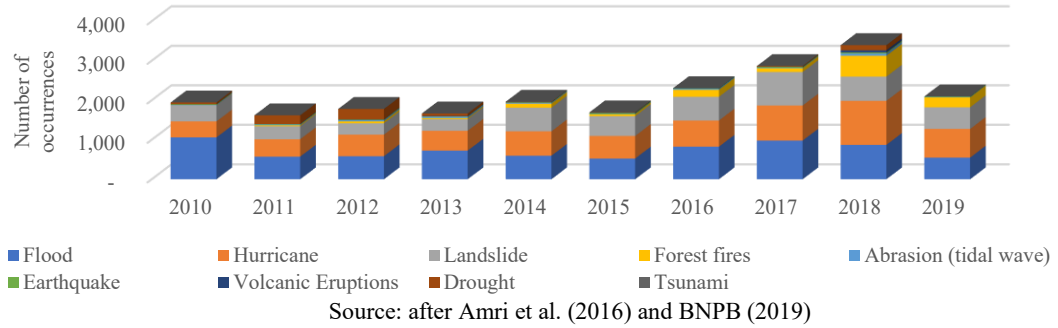


Figure 4.8 Extreme anomalous in air temperature seen in 2016 against data from 1981-2010 (after BMKG, 2019)



	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Geology	76	126	158	141	292	840	356	325	317	634	545
Hydrometeorology	539	679	729	979	830	1,129	1,299	1,516	1,431	1,362	1,155

Geology:e.g. volcanic erruptions, tsunami; Hydrogeology: e.g. flood, hurricane, landslide..

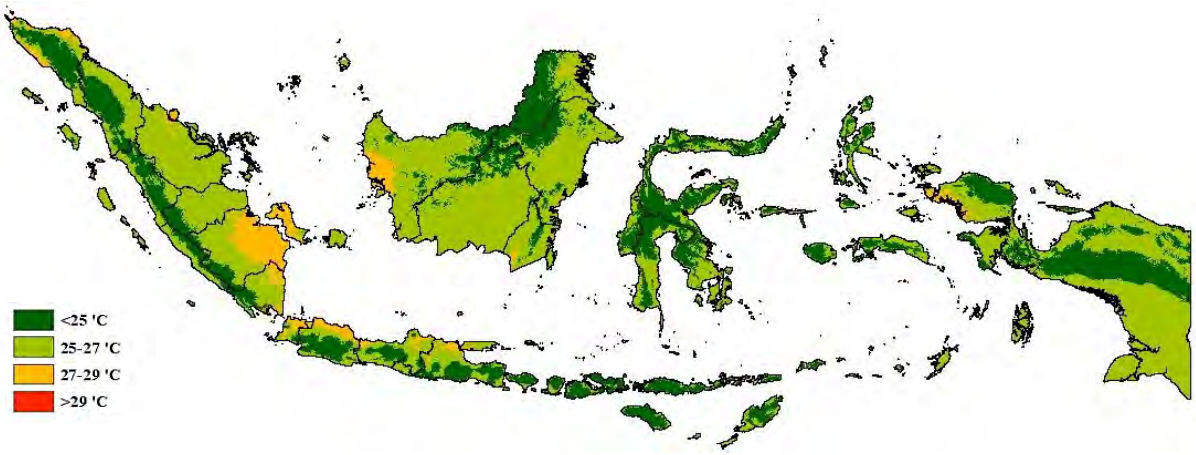


Source: after Amri et al. (2016) and BNPB (2019)

Figure 4.9 Number of disasters in Indonesia

4.3 Climate Change and Extreme Weather Scenario

Changes in climate parameters may be projected using various scenarios and assumptions (IPCC, 2014b). To date, several international climate projection scenarios have been developed by the Intergovernmental Panel on Climate Change (IPCC), an international scientific panel on climate change founded by The Meteorological Organization (WMO) and the United Nations Environment Program (UNEP). The IPCC offers four alternative scenarios following the greenhouse gas Representative Concentration Pathways (RCP), i.e. RCP2.6, RCP4.5, RCP6.0, and RCP8.5. However, since there is uncertainty about the future concentration of greenhouse gases (GHG), the best projection should fall between the very pessimistic (RCP 8.5) and very optimistic (RCP 2.6) scenarios (IPCC, 2014a). Correspondingly, as Indonesia believes that the progression of global warming can be partially slowed through environmental and technological mitigations, Indonesia uses RCP 4.5 which specifies a mid-range level of optimism for climate projection scenarios (BMKG, 2018c). Therefore, this research uses the IPCC RCP4.5 projection scenario to ensure that the research outcomes can be synchronised with the strategic policy in Indonesia. By using Arc-GIS software, the IPCC RCP4.5 climate projection scenario for annual temperature and precipitation in Indonesia was calculated, and the results can be seen in **Figure 4.10** and **Figure 4.11**.



a) Historical data: average annual temperature (1970-2000)

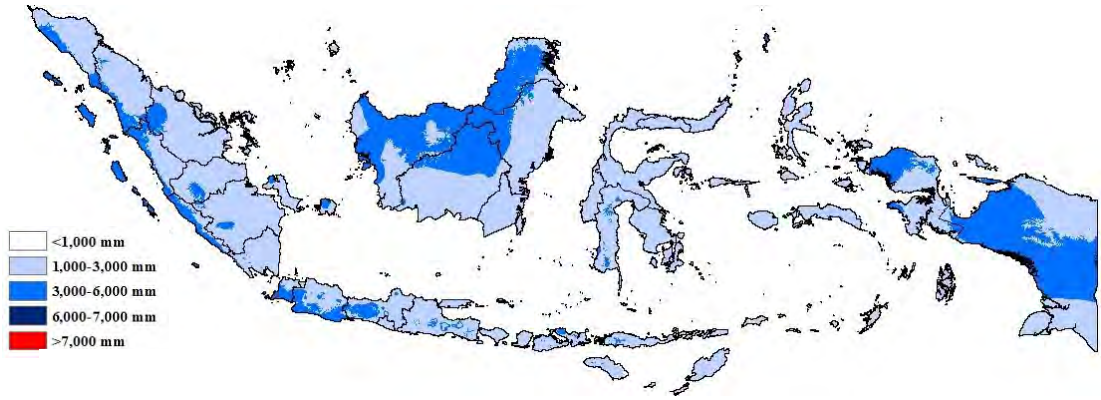
Figure 4.10 Historical data and projection scenario of annual temperatures in Indonesia



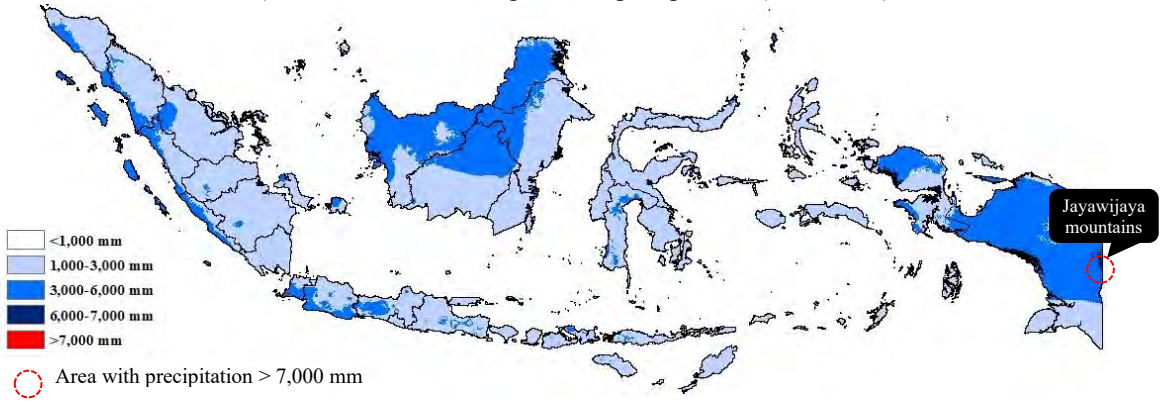
b) Projection of average annual temperature in the year 2050 based on IPCC AR5 scenario

Source: a. based on BMKG, 2014; b. based on CCAFS and IPCC, 2014

Figure 4.10 (Continue)



a) Historical data: average annual precipitation (1970-2000)



b) Projection of average annual precipitation in the year 2050 based on IPCC AR5 scenario

Source: a. based on BMKG, 2014; b. based on CCAFS and IPCC, 2014

Figure 4.11 Historical data and projection scenario of annual precipitation in Indonesia

Based on IPCC RCP4.5 climate projection (see **Figure 4.10b**), the average annual temperature in Indonesia will have increased to 30 ^{0}C by the year 2050, with the highest temperatures predicted in Jakarta, Palembang and Pontianak. Likewise, the projected precipitation also

shows an increasing pattern. **Figure 4.11b** illustrates that the number of regions with rainfall of 3,000 to 6,000 mm/year will increase, particularly for Kalimantan and Papua islands. The area with the highest precipitation will likely be the Jayawijaya mountains, Papua Barat.

In terms of extreme weather events (EWEs), as the climate parameters increase, the probability of EWEs occurring increases, both in terms of severity and frequency. However, the EWE projection scenario has not yet been accommodated in the IPCC climate modelling. Thus, it is assumed that EWEs will occur in Indonesia, and the impacts on road pavements and accessibility are simulated and elaborated further in **Chapter 4.4** and **Chapter 8.7**.

4.4 The Impact of Changes in the HDM-4 Climate Parameters on Road Conditions

4.4.1 Climate Parameters in the HDM-4

For finding out the technical impact of climate change to the road pavement, the HDM-4 simulates the potential impact of changing climate parameter on the overall road condition by using the road deterioration model. The change in environmental features such as precipitation and air temperature may be accommodated by altering the inputs of climate configuration in the HDM-4 model to meet the current and projected climate patterns in Indonesia. The HDM-4 climate parameters and its default values can be seen in **Table 4.2**.

Table 4.2 The default value of climate parameter in HDM-4 version 2

Climate factor		Climate Zone				
Precipitation	Moisture classification	Arid	Semi-arid	Sub-humid	Humid	Per-humid
	Moisture Index	-80	-40	0	60	100
	Duration of dry season [months]	10.8	9	6	3	1.2
	Mean monthly precipitation [mm]	15	50	100	175	210
Temperature	Temperature classification	Tropical	Subtropical		Temperate	
			hot	cool	cool	freeze
	Mean temperature [^{0}C]	27	22	18	12	8
	Avg. Temperature range [^{0}C]	15	17	13	15	20
	Days T>32 ^{0}C [days]	90	60	30	15	10
	Freeze Index [C-days]	0	0	0	55	220
	Percentage of Time Driven:					
	▪ On snow covered roads [0-100]	0	0	0	10	20
	▪ On Water covered roads [0-100]	20	10	15	5	10

Source: HDM-4 Manual, Morosiuk et al. (2004)

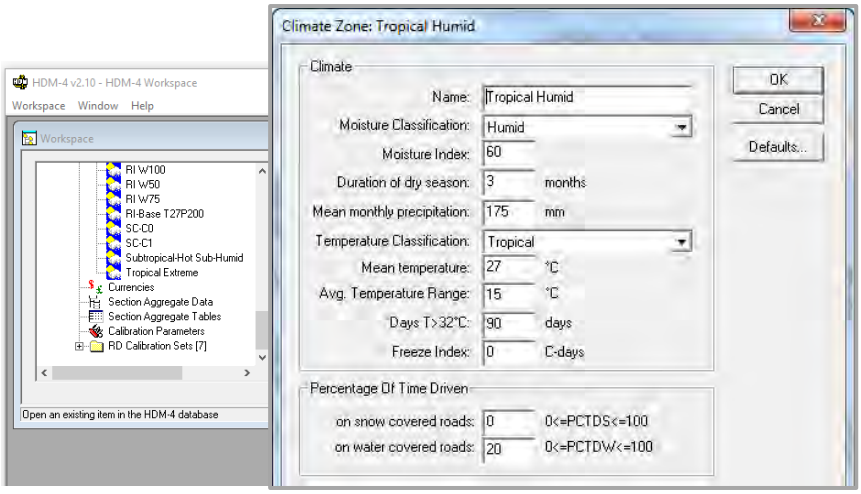
4.4.2 The Scenario of Changing in Climate Parameter

Following the climate projection for Indonesia (see **Chapter 4.3**), the changing parameters for representing climate change and extreme weather scenario may be seen in **Table 4.3**. Scenario zero, e.g. T0, represents current temperature conditions, scenario 1 to 3 represents an increase in climate parameters, and scenario four represents a decrease in climate parameters. As shown in **Figure 4.12,** the climate scenarios are used to feed the HDM-4, i.e. as the input to simulate the impact on road conditions from changes to individual climate parameters.

Table 4.3 Scenarios for changing climate parameters

Code of Scenario	Changes in climate parameters for the HDM-4 inputs			
	Mean temperature (T, ^{0}C)	Mean Precipitation (P, mm/month)	Days >32 ^{0}C (D, days)	Driving on water covered roads (W, %)
0 [a]	27	200	90	20
1	30	250	180 [b]	0
2	35 [b]	500 [b]	270 [b]	50 [b]
3	50 [b]	750 [b]	365 [b]	75 [b]
4	25	175	0	100 [b]

a. base scenario (T0, P0, D0, W0);
b. extreme condition scenario based on Indonesia as a case study



Source: screenshot from HDM-4 software

Figure 4.12 Altering climate parameters inputs in the HDM-4 tool

4.4.3 Road Representatives

This section intended to briefly illustrate how changing the input of climate parameters in the HDM-4 affects the overall performance of road networks. As a simple case study, road

networks in Indonesia may be distinguished and represented by bituminous (asphalt) and gravel roads. In the assessment, each road category is simulated using 1,000 km of RAT1R1 and RGT1R1 road (see **Appendix B**) to find out how the changes in climate parameters affect the condition of these two common road categories.

4.4.4 The Impact of Precipitation on Road Condition

Based on the HDM-4 simulations, the results show that the higher precipitation, the worse road conditions become. The increased precipitation has a significant impact on the overall condition of the gravel road network, but the impact is less significant on the asphalt road network. For the bituminous road network, as shown in **Figure 4.13**, the condition of the roads is always at a satisfactory level, i.e. below the IRI threshold (IRI=8), for all increased precipitation scenarios (P0, P1, P2, and P3) when the IRMS maintenance standards were applied (solid line graph) over the twenty-year analysis period. However, a satisfactory level of road condition cannot be achieved when the Do Nothing (DN) scenario is applied (dashed line graph), mainly for the second decade of the analysis period (year-11 to year-20). In terms of roughness progression, the simulation results show a pattern that the line graph was typically grouped following the climate zone of precipitation, e.g. humid and per humid. The line graph for P0 were typically merged with P1 while P2 merged with P3.

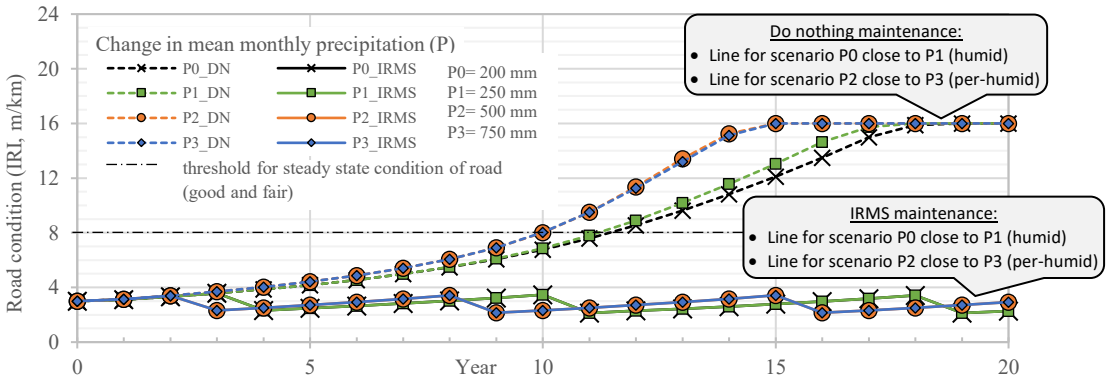
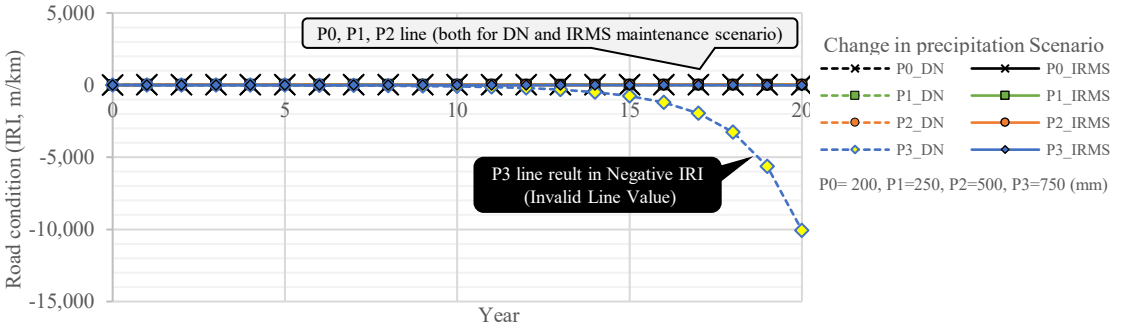
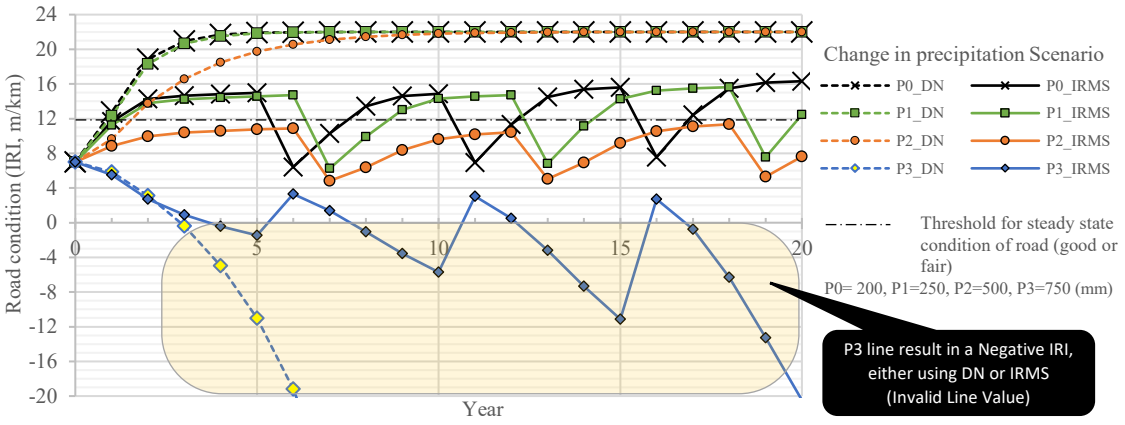


Figure 4.13 The impact of changes in precipitation on bituminous road conditions

Concerning the gravel road network, the result of the HDM-4 simulation shown an unusual pattern of roughness progression, mainly for the P3 precipitation scenario and using both DN and IRMS maintenance standards (see **Figure 4.14a**). Based on the more detailed figure, a positive value of roughness outputs was still identified in the early years of analysis, e.g. year one to year three on scenario P3. However, the roughness value fluctuates and becomes negative in subsequent years (see **Figure 4.14b**). Although the HDM-4 as a tool may still give outputs (e.g. roughness progression for the twenty years of analysis), the negative output of roughness indicates that an error occurred because in theory roughness (IRI) should always be a positive value. In this case, the HDM-4 tool was found incapable of accommodating such extreme values as inputs in the simulation.



a. Full scale of figure presentation on IRI value (Y axis)



b. Normal scale of figure presentation on IRI value (Y axis)

Figure 4.14 The impact of changes in precipitation parameter on gravel road conditions

According to the HDM-4 deterioration model, as environment load, climate may damage road pavement through cracking, disintegration, deformation, and roughness (see **Table 4.4**). Furthermore, the increases in climate parameters may worsen the overall condition of roads and follow the HDM-4 road deterioration scheme, as shown in **Figure 4.15** and **Figure 4.16**.

Table 4.4 Type of distress in the HDM-4 models influenced by climate parameters

Distress Mode	Distress type
Cracking	Structural, Reflection, Transverse thermal
Disintegration	Raveling, Potholing, Rutting (surface wear), Edge break
Deformation	Rutting structural, Rutting - plastic flow
Profile	Roughness
Friction	Texture depth, Skid resistance

Source: HDM-4 manual by Morosiuk et al. (2004)

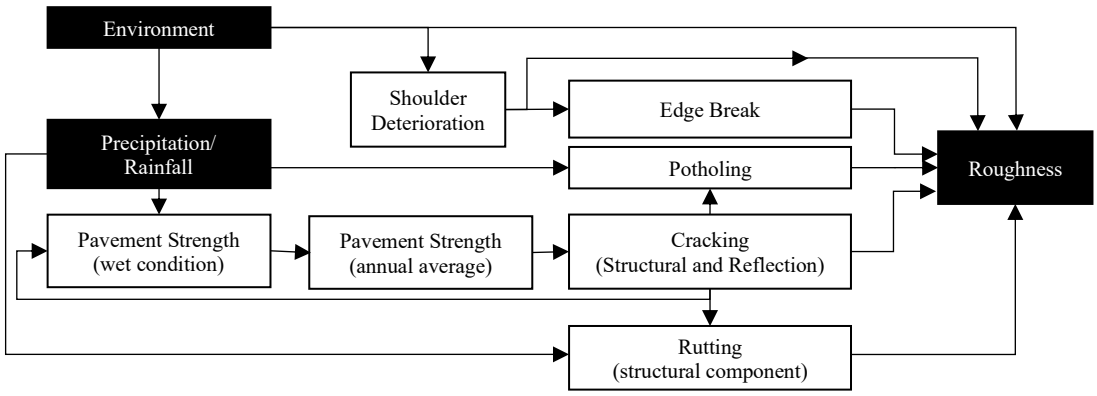


Figure 4.15 Deterioration scheme of bituminous road influenced by precipitation in HDM-4 (resumed from HDM-4 manual, Morosiuk et al., 2004)

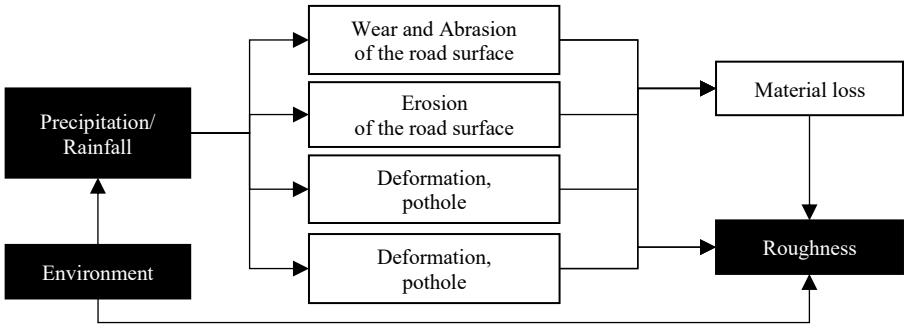


Figure 4.16 Deterioration scheme of gravel road influenced by precipitation in the HDM-4 (resumed from HDM-4 manual, Morosiuk et al., 2004)

In the HDM-4 road deterioration formula, precipitation parameters are inputted in the form of mean monthly precipitation. The value is then categorised based on moisture classification and represented as environmental coefficient "m". Accordingly, the value of coefficient “m” remains constant unless the increase in precipitation also shifts the climate zone (see **Table 4.5**). It means that the impact of increased precipitation on road conditions in Indonesia will be theoretically significant when the precipitation becomes more than 250 mm/month and the climate zone shifts from humid to per-humid, i.e. the value of the environmental coefficient ‘m’ increases from 0.025 to 0.030.

Table 4.5 The value of environmental coefficient ‘m’ in HDM-4 version 2

		Temperature classification and range (°C) [b]					
		Tropical (20 to 35)	Sub-tropical		Temperate		
			Hot (-5 to 45)	Cool (-10 to 30)	Cool (-20 to 25)	Freeze (-40 to 20)	
Moisture classification and the range of mean monthly precipitation (mm) [a]	Arid (0 to 25)	0.005	0.010	0.015	0.020	0.030	‘m’ increases
	Semi-arid (25 to 66)	0.010	0.015	0.020	0.030	0.040	
	Sub-humid (66 to 133)	0.020	0.025	0.030	0.040	0.050	
	Humid (125 to 250)	0.025	0.030	0.040	0.050	0.060	
	Per-humid (> 200)	0.030	0.040	0.050	n/a	n/a	
		‘m’ increases					**‘m’**

a. The coefficient ‘m’ increases as the precipitation increases. b. The coefficient ‘m’ increases as the temperature decreases

Overall, the HDM-4 simulation results pointed out that gravel roads are more susceptible to increases in precipitation than bituminous roads, and they cannot withstand the climate change scenarios. The increase in precipitation will increase coefficient “m” as environment load and worsen the overall road conditions. However, the impact will remain minimum unless the increase in precipitation also shifts the climatic zone.

4.4.5 The Impact of Temperature on Road Condition

In terms of temperature, based on the theoretical concept of pavement engineering, along with precipitation, increases in temperature should quicken the progression of road deterioration (Huang, 2004). Depending on the increased value, the impact may not be significant on gravel

roads. However, it will be significant on bituminous roads because they are made of asphalt, a thermoplastic material used as a binder for the road pavement. The HDM-4 simulation shows that there is no significant impact on the overall condition of bituminous and gravel roads networks from changing temperature scenarios (see **Figure 4.17**).

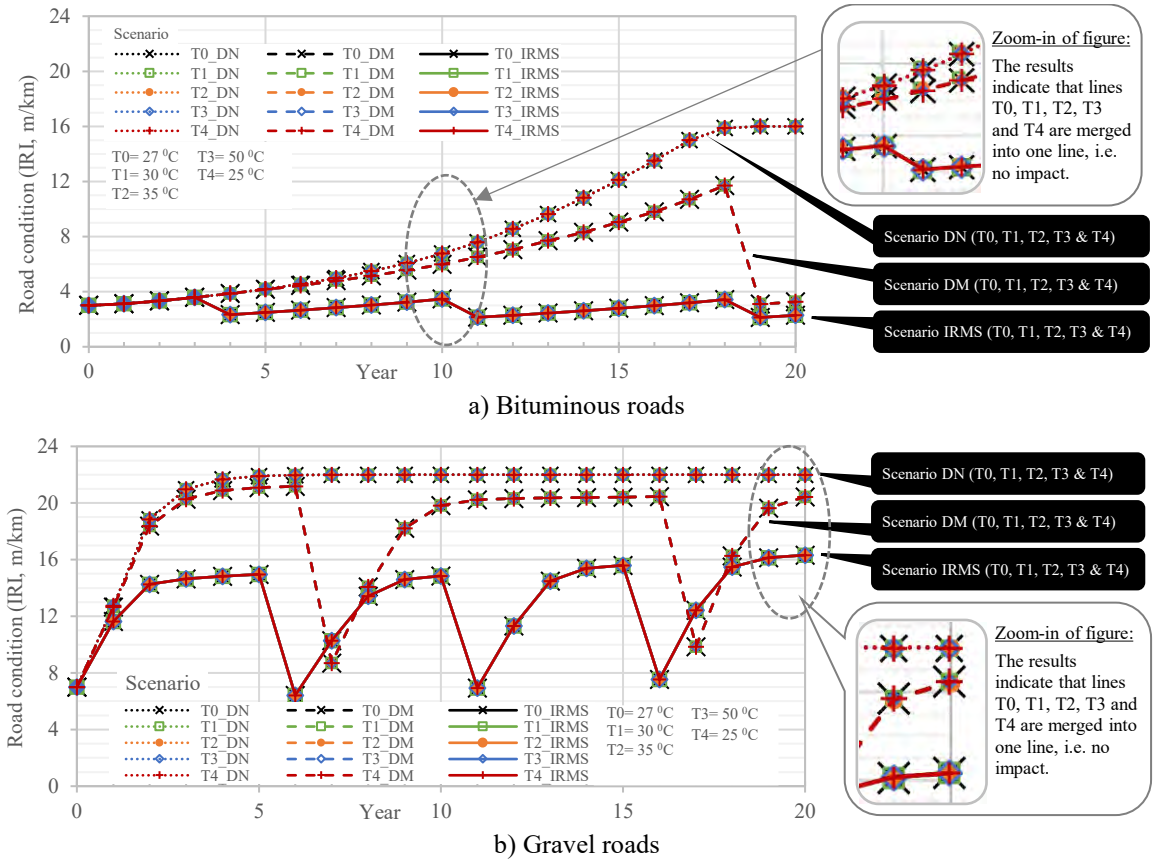
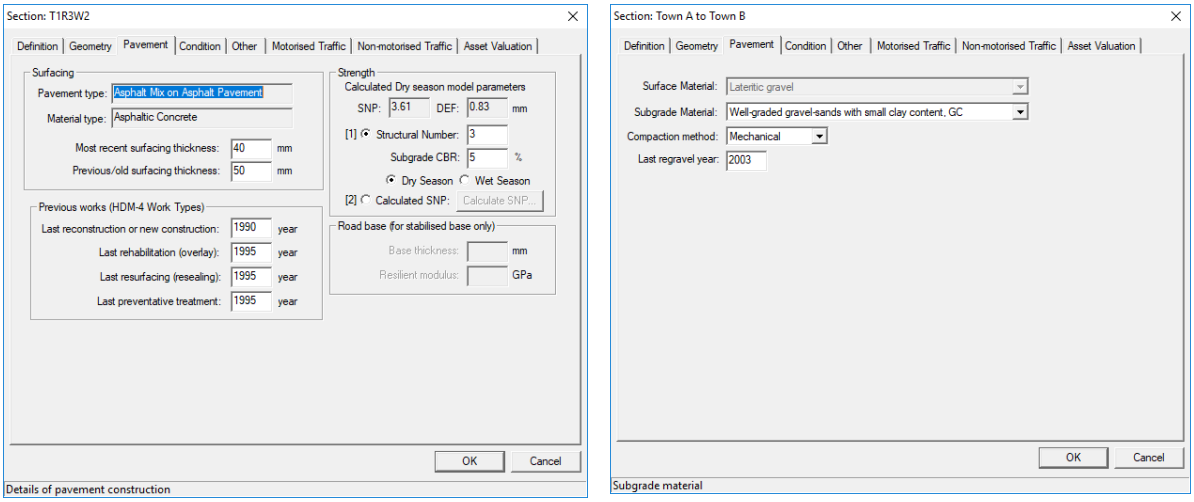


Figure 4.17 The impact of temperature changes on road conditions

Figure 4.17 shows that the roughness progression line for all scenarios (T0, T1, T2, and T3) almost merged to become a single line regardless of the applied scenario of road maintenance in the simulation, e.g. do nothing (DN), do minimum (DM), and IRMS standards (IRMS). This pattern of results was found for both bituminous and gravel road networks. It could be because the HDM-4 assumed that the materials for road pavement have been selected and designed according to local climate patterns. This assumption is confirmed by the fact that there is no specification data of the type of asphalt material required for the HDM-4 input (see **Figure**

4.18). Furthermore, because Indonesia is already located in the highest zone for temperature (tropical area), a further increase in temperatures does not result in a shift-up in climate zone, i.e. the value of the environmental coefficient (m) as climate load remains the same (see **Table 4.5**). Consequently, there is no substantial impact found on the overall condition of bituminous and gravel road networks in Indonesia due to the increased temperature scenario.



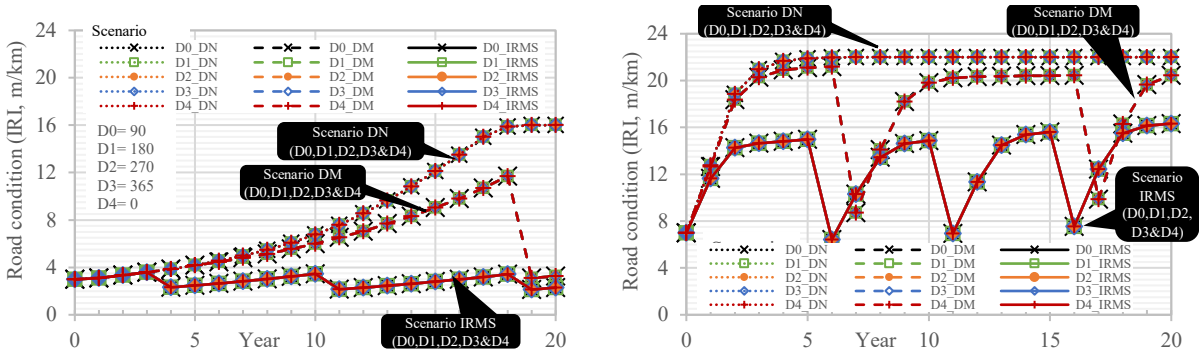
a) Bituminous roads b) Gravel roads

Figure 4.18 Pavement parameters as HDM-4 inputs

Based on road engineering theory, the impact of rising temperatures should not be significant if the value is still within the range of asphalt working specifications. Indonesia has a *Weighted Mean Asphalt Pavement Temperature* (WMAPT) of 38 ^{0}C for mountainous areas to 42 ^{0}C for coastal areas (Kurnia, 2017). Therefore, the use of Asphalt Penetration 60/70 in pavement design (assuming WAMPT 41^{0}C) may be sufficient because based on the ASTM and AASHTO specification standards, the softening point for asphalt pen 60/70 (i.e. 49-56 ^{0}C) is higher than the maximum temperature in Indonesia. However, the consideration to use additional materials to increase the maximum working temperature or use another type of asphalt material could be considered to manage a further increase in temperature, e.g. WAMPT 50 ^{0}C or extreme weather events.

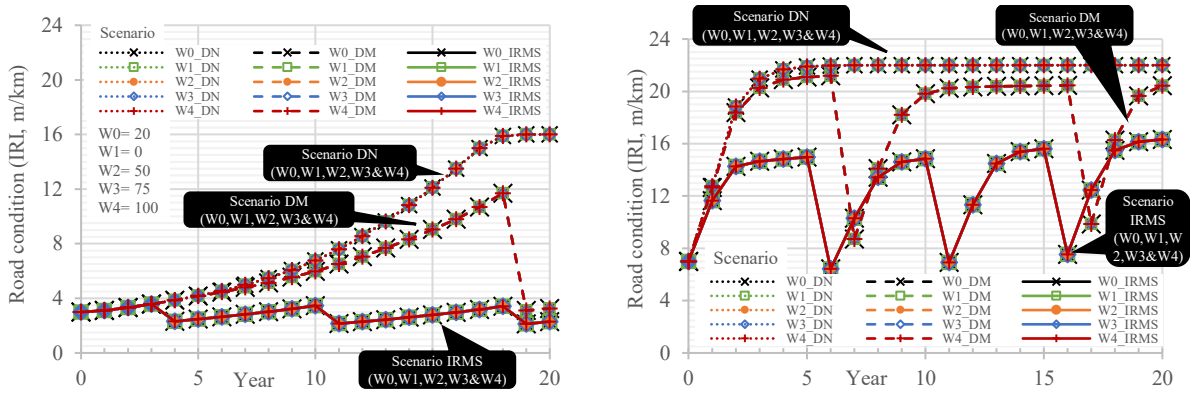
4.4.6 The Impact of Other HDM-4 Climate Parameters on Road Condition

Based on climate inputs in the HDM-4, the other parameters that influence road performance are the number of days when the temperature exceeds 32 ^{0}C (D) and the percentage of driving done on water covered roads (W). However, the result of the HDM-4 simulation indicated that there is no significant impact of changes in those two parameters on the overall road condition because the simulation gives the same output value for any change to the D or W parameters. **Figure 4.19** and **Figure 4.20** shows that the line of road condition for all change scenarios in the D and W parameters (i.e. scenario *D0, D1, D2, D3 & D4* and scenario *W0, W1, W2, W3 & W4*) using the do nothing (DN) maintenance scenario are merged into a single line. Similarly, this pattern also occurred when they were simulated using do minimum (DM) and IRMS maintenance standards (IRMS).



a) Bituminous roads b) Gravel roads

Figure 4.19 Changes in the number of days when the temperature exceeds 32 ^{0}C



a) Bituminous roads b) Gravel roads

Figure 4.20 Changes in the percentage of driving done on water covered roads

According to the HDM-4 model, it happens because parameter D (DAYS90) is only applied for concrete pavements deterioration models, e.g. joint faulting and spalling, while parameter W is applied in the rolling resistance model which corresponds to the road user costs (Morosiuk et al., 2004). Based on road engineering theory, these parameters can influence the overall road condition. However, the impact may not be significant, or it has been anticipated and addressed by the current road design standards, e.g. minimum longitudinal drainage gradient of road pavement. Thus, due to simplification in the HDM-4 model, neither the D nor the W parameter have been included in the HDM-4 tool to simulate the bituminous and gravel road conditions. Consequently, it can be concluded that in the current road asset management appraisal, the D and W parameters do not give a direct impact on the overall condition of bituminous and gravel road networks.

Overall, based on the HDM-4 simulations, the results show that increases in precipitation have the most significant impact on the overall road condition compared to the other climate parameters. The change in the HDM-4 climate parameters may negatively impact road condition as it increases the environment load. The impact may be low when the change is not significant, and the value of parameter remains in the same climate zone. However, the impact becomes significant when the increase shifts the climate zone, e.g. from tropical humid to tropical per-humid (see **Chapter 4.4.4**).

In terms of road maintenance scenarios, the results of the HDM-4 simulation show that the current Indonesian road maintenance standards (IRMS) are adequate to withstand the increase in precipitation and temperature scenarios on the asphalt road network. However, they were found to be insufficient for the gravel road network. Accordingly, it is advisable to improve the gravel road maintenance standards in the IRMS to adapt to the increase in extreme climate

scenarios and ensure an optimal level of road performance in Indonesia. The proposed revisions to the gravel road maintenance standards (IRMS) are presented in **Chapter 8.8.1**.

4.5 Simulation of Climate Change Scenarios in the HDM-4

4.5.1 Road Representatives

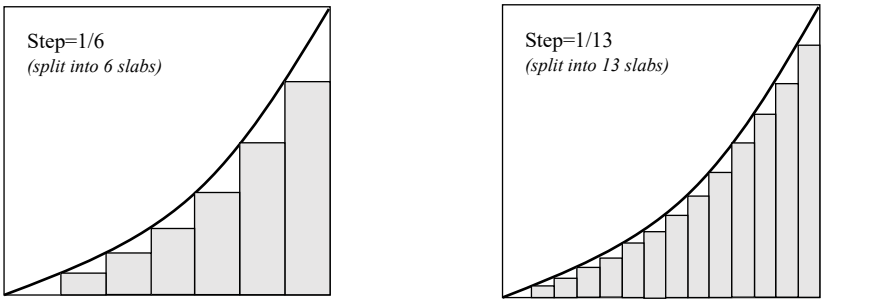
In this section, as the case study, the analysis uses 1,000 km of road consisting of 60% bituminous road and 40% gravel, which is the typical distribution of road assets in Indonesia. Two alternatives of maintenance standards i.e. do nothing (DN) and Indonesian maintenance standards (IRMS), were applied to see how effective the IRMS standard is in dealing with climate change scenarios in Indonesia.

4.5.2 Approach to Simulate Climate Change Scenario in the HDM-4

The HDM-4 is a standard decision support system in road investment which is typically used to simulate the future condition of road assets. Based on the climate change scenario in **Chapter 4.3**, the climate parameters should be gradually increased each year during the analysis periods. However, in the latest version of HDM-4, i.e. version 2, the road deterioration model may only be simulated using a static climate (SC) as the basis for the assumptions (Morosiuk et al., 2004; Anyala, 2011). In the SC approach, the climate parameters are assumed to be constant (no alteration) during the analysis period. Consequently, to simulate the effects of climate change, road managers may only use the worst climate scenario or climate value at the end of the analysis period as the climate input for the HDM-4.

As an alternative approach, the dynamic changes in climatic parameters may be adjusted by breaking down the period of analysis into smaller time-slices, e.g. every five years (see **Chapter 3.5**). Afterwards, the climate parameters in each time-slice may be altered to follow the dynamic pattern of climate scenarios. This dynamic climate (DC) technique adopts the use of integrals to calculate the area under a curve, i.e. by splitting or breaking down the curve into thin vertical

slabs (see **Figure 4.21**). Based on the integral theory, the more slabs, the better the results, i.e. splitting the area into thirteen slabs produces more accurate results than splitting it into six slabs (Smirnov and Smirnov, 2006).

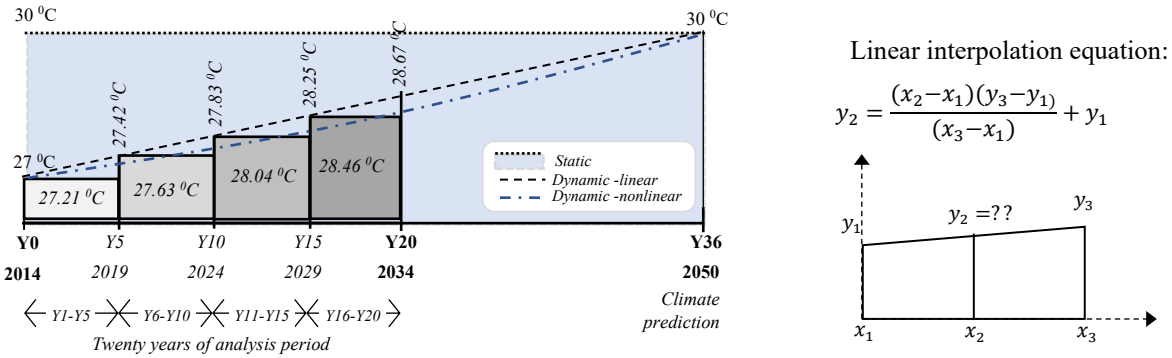


a. Split the curve area into six slabs b. Split the curve area into thirteen slabs

Figure 4.21 Integral theorem in calculating the area below a curve

4.5.3 The Application of Static and Dynamic Climate Input in the HDM-4 Model

In a higher temperature scenario, the temperature for every 5-year slab may be calculated using a linear interpolation technique following the interpolation equation, as shown in **Figure 4.22b**. For instance, the temperature from 2009 (Y5) may be interpolated based on the temperature data from 2014 (Y0), and 2050 (Y36), i.e. Y5=27.42 ^{0}C. Likewise, the precipitation parameter can also be calculated using the same method. The results of interpolation can be seen in **Table 4.6**.



a. The scenario of splitting the climate period b. Interpolation equation

Figure 4.22 Scenario of splitting the period for changing climate parameters

Table 4.6 Scenario of splitting the climate change period

Parameter	Dynamic climate (a slab of climate period) [a]				Static climate [b]	
	Y1-Y5	Y6-Y10	Y11-15	Y16-Y20	C0	C1
Temperature (^{0}C)	27.21	27.63	28.04	28.46	27	30
Mean monthly precipitation (mm)	203.47	210.42	217.36	224.31	200	250

a. Yn = Year n from analysis period, n = 1,2,.....,20.
b. C0= existing climate (year 2014), C1=predicted climate in the next 20 years (year 2050)

Based on the dynamic climate (DC) input approach, the HDM-4 outputs from scenario Y1-Y5, e.g. road condition in year five (Y5=2019), are used to feed the next slab of the HDM-4 analysis, i.e. as the inputs for scenario Y6-Y10. This procedure applies for the next slabs of simulation. The data that needs to be re-inputted in the sequential slabs of the HDM-4 simulation includes traffic volume, pavement strength, and road conditions such as roughness, all structural cracks, ravelling, edge break, rut depth, structural number, and gravel thickness (see **Table 4.7**)

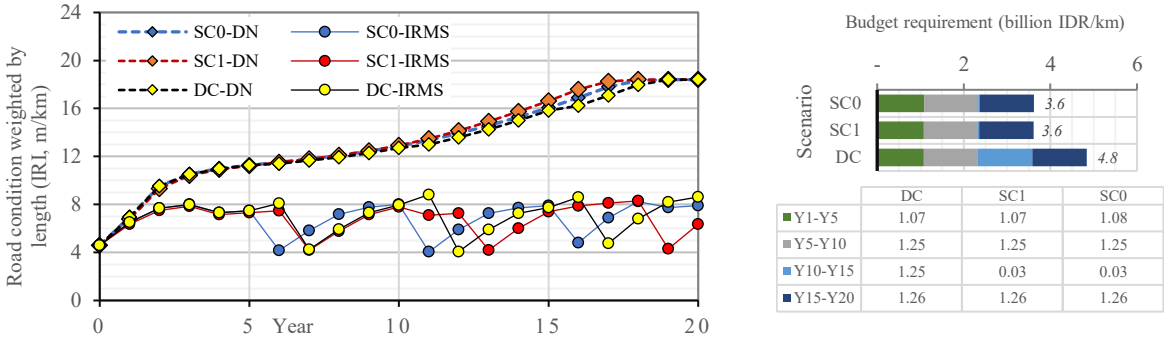
Table 4.7 Road condition parameters at the end of each 5-year analysis

End of year	Maintenance scenario	Bituminous roads					Gravel roads	
		IRI Avg. (m/km)	All Str. Cracks (%)	Ravelling (%)	Edge Break (sq. m)	Rut Depth (mm)	IRI Avg.	Gravel Thick. (mm)
0 [a]	DN	3.00	0.00	0.00	0.00	0.00	7.00	200.0
	IRMS	3.00	0.00	0.00	0.00	0.00	7.00	200.0
5 [a]	DN	4.18	19.46	52.97	171.07	3.31	21.90	134.5
	IRMS	2.48	0.00	0.00	20.42	0.85	14.95	152.2
10 [a]	DN	6.51	86.99	6.52	454.70	4.48	22.00	70.9
	IRMS	3.46	9.45	21.06	33.72	1.82	14.68	162.2
15 [a]	DN	11.70	85.83	0.00	992.22	9.37	22.00	7
	IRMS	2.63	0.00	0.00	55.89	1.16	15.41	162.2
20	DN	16.00	82.00	0.00	1,260.00	16.65	22.00	0
	IRMS	3.64	8.18	20.11	93.52	1.33	16.11	162

a. These outputs are used to feed (input) the subsequent 5-year period of HDM-4 simulations.

Based on the HDM-4 simulation, the results indicated that the SC and DC method generated almost identical outputs during the first decade of analysis (Y1-Y10), but started to produce different output values in the next decade of analysis (Y11-Y20). When IRMS standards are applied (see **Figure 4.23a**), it is noticed that for optimising the NPV/Cost during the 20 years analysis period, the DC-IRMS shows an earlier drop of roughness (e.g. in Y12 and Y17) than the SC1-IRMS, which experiences it in Y13 and Y19. This result indicates that at the beginning

of each simulation period, the HDM-4 lifecycle cost analysis (LCCA) is always keen on requesting a higher budget (as investment) to optimise the economic life of an asset and to minimise the total maintenance costs over the 20-year analysis period. Accordingly, if the analysis period is divided into four slabs, the DC method suggests investment four times, in Y4, Y7, Y12 and Y17 (see **Figure 4.23a),** regardless of whether an asset needs to be repaired. Consequently, the DC method results in a higher budgetary requirement (see **Figure 4.23b**).



	DC	SC1	SC0
Y1-Y5	1.07	1.07	1.08
Y5-Y10	1.25	1.25	1.25
Y10-Y15	1.25	0.03	0.03
Y15-Y20	1.26	1.26	1.26

a. Road condition

b. Budget requirement (IRMS)

Figure 4.23 Road condition Vs approach of climate change input in HDM-4

Similar to the IRMS scenario, the Do-Nothing (DN) scenario shows the same pattern of results, i.e. the road condition is typically similar during the first decade, before changing over the following decade. Initially, this pattern might look logical, but when assessing the detail of roughness progression, it violates the road deterioration principle. Based on road engineering theory, pavement conditions should be worse when the pavements have to withstand extra climate burdens, e.g. higher temperature or precipitation (Papagiannakis and Masad, 2017; Kodippily et al., 2018). Accordingly, the roughness progression line for the DC-DN scenario should be situated between the SC0-DN and SC1-DN scenarios. Nevertheless, it lies lower than the two static climate options. This result pointed out that the DC method is not suitable for long-term analysis of road assets.

The results of HDM-4 simulation indicate that the climate model in the HDM-4 tool was unable to accommodate increasing climate pattern inputs in the life cycle cost of analysis. Some adjustments and simplification are required to address it. In terms of climate input, it was found that the use of SC method is better than DC method for simulating climate change in the HDM-4 tool. In theory, the dynamic climate (DC) method as an alternative approach for inputting the changes in climate parameters may sound logical. However, in the application of HDM-4 lifecycle cost analysis (LCCA), the DC method produces biased outcomes because it performs a short-term analysis instead of a long-term one. In this case, the number of looping simulations in the optimisation procedure (e.g. scenarios of investment year and roadwork alternatives) of the DC method was much less than those simulated in the SC method. Consequently, the optimisation outcome using the DC method may be less effective and efficient because assets tend to be repaired earlier than required. In terms of model implementation, the DC method requires massive data, and the data outcome should be re-input sequentially by year. The complicated and more time-consuming work required for the DC method makes it less practical than the SC method.

Furthermore, as described in **Chapter 2.3**, climate change is based on probability. It means that when the changes are difficult to control, the use of future climate parameters (which are typically higher than current conditions) as static climate input (SC method) in the HDM-4 simulation may also be interpreted as a safety factor to anticipate climate change. Therefore, the SC method for use in the current HDM4 tool was found more appropriate than the DC method to represent and simulate the potential impact of climate change on road conditions.

4.6 Summary

In terms of simulation methods, simulating climate change using a sequential approach (dynamic method) to address the static climate assumptions in the HDM-4 was evaluated and

proven to be inappropriate for long-term analytic applications. The dynamic method (DC method) results in a different optimisation regime associated with the economic life of road assets. Besides, it requested detail and large amounts of data which made it less practical in implementation. The results to date show that the SC method is the most suitable approach to represent climate change in HDM-4 simulation procedures as it has been proven it can accommodate the climate change scenarios and lifecycle cost analysis (LCCA).

In the case of study, the overall results indicate that the existing Indonesian maintenance standards (IRMS) can cope with the change in climate scenario if the road network is kept in a steady-state condition (e.g. IRI $\leq$ 8 m/km). Precipitation was found to be the most sensitive parameter influencing road conditions. Based on the HDM-4 simulation, unlike a sealed road, gravel roads are susceptible to climate load and cannot withstand the climate change scenarios. Accordingly, gravel roads could be upgraded to bituminous roads as part of future climate change adaptation strategies. Also, the type of road pavement should be included as an additional parameter for measuring accessibility levels to ensure reliability of access in response to changing climate conditions.

CHAPTER 5

DEVELOPMENT OF ROAD NETWORK ACCESSIBILITY INDEX

5.1 Introduction

This chapter presents the conceptual model and the associated procedure to develop a road infrastructure-based accessibility model. The chapter comprises ten sections. Initially, it illustrates the overall approach and procedure to develop an accessibility model using the composite indicators method. This procedure is elaborated in more detail in the following sections, including the theoretical framework, indicator selection, and some alternative forms of model to calculate the accessibility index. The last section provides a resume about the development procedure of the accessibility model.

5.2 Overall Approach

As described in **Chapter 3**, the accessibility model is developed using composite indicators and statistical analysis following the "Handbook on Constructing Composite Indicators" from the Organization for Economic Co-Operation and Development (OECD). This method was selected because of the complex features of accessibility, which are multidimensional but should be quantified and aggregated into a single index. In general, the composite indicators procedure to develop the accessibility model is illustrated in **Figure 5.1**.

According to the composite indicators' procedure, the most fundamental step is developing the theoretical framework of the accessibility model. This step provides the conceptual design and the basis for the selection and combination of single indicators into a meaningful composite indicator under the principle of fitness for purpose (Nardo et al., 2008). First, the objective for *'what'* and *'who'* the accessibility model is intended for should be clearly described. Once it is

confirmed, a definition of the accessibility index is defined to give a clear sense of what the index is measuring (Vértesy, 2016). Subsequently, some parameters which may influence the level of accessibility should be identified as components to measure the accessibility index. Since the value of each parameter may have a different unit of measurement, the value may then be normalised using a suitable normalisation and weighting-technique.

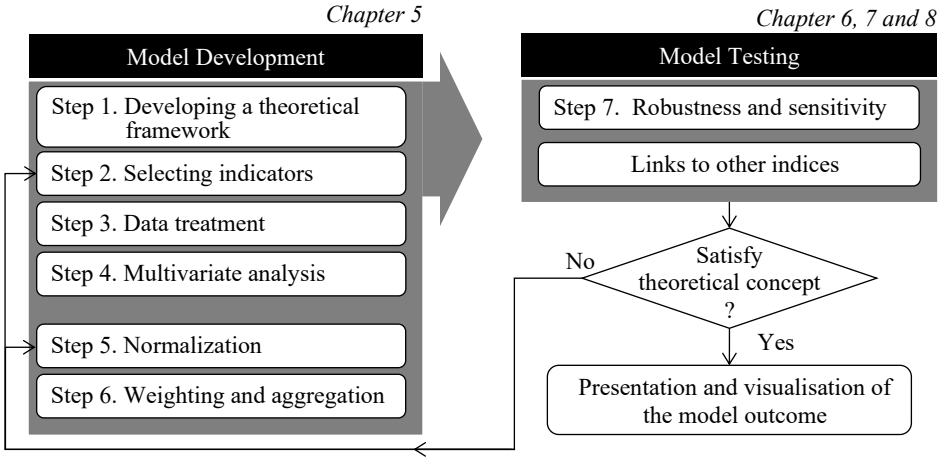


Figure 5.1 Procedure to develop composite indicator model (adapted from Nardo et al., 2008)

5.3 Step 1: Theoretical Framework of the RNAI Model

5.3.1 Aims and Definition of the RNAI Model

The development of the accessibility model in this research aims to seek an appropriate model for use by authorities to support the role of road managers as a tool for regional development through accessibility management. As the role of a road authority may be limited within the scope of road asset management, the components of the accessibility model must be specific and focus on road infrastructure features and their condition (see **Figure 5.2**). Thus, as stated in **Chapter 3**, the accessibility model at hand seeks to determine the road network accessibility index (RNAI), which is defined as 'the extent to which road network infrastructure ease road users to reach their destination(s) throughout the year within a particular region.'

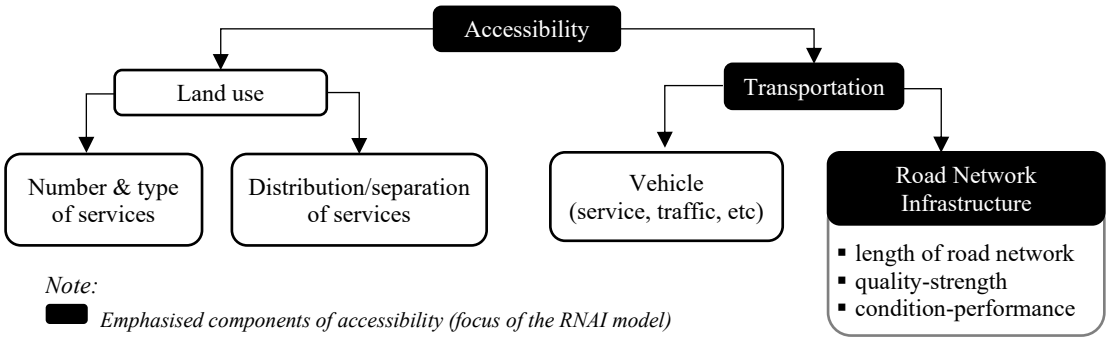


Figure 5.2 The RNAI measurement focuses on road infrastructure features

5.3.2 Units of Analysis

A unit of analysis is the entity that is analysed in a study (Long, 2004). It could be a group, individual, or geographical unit such as a town or state. Harris (2018) pointed out that the unit of analysis explains the focus and level of analysis of a study. Remoteness or accessibility is seen as a geographic variable, a characteristic of places rather than a direct aspect of populations (The Commonwealth Department of Health and Aged Care, 2001). Correspondingly, as explicitly stated in the definition, the focus of the RNAI measurement is the accessibility to all locations in need of transport services within an area (integral accessibility). It means that the unit of analysis represents a geographical area based on administrative, geospatial, or artificial boundaries.

5.3.3 Conceptual Design of the RNAI Model

The theoretical framework of the RNAI is guided by the literature review on the previous models of accessibility such as the Hansen Accessibility Index, the Rural Access Index (RAI), the Accessibility/Remoteness Index of Australia (ARIA) and the road density from the World Bank (see **Chapter 2**). To develop a robust infrastructure-based accessibility model, the model should not only be theoretically correct but should focus on addressing road asset management problems that could affect accessibility (Hay and Trinder, 1991). Thus, the model should explicitly consider the condition of road infrastructure and its economic life using the concept

of equity. Furthermore, since the model is intended to be implemented in developing countries, the main characteristics of developing countries, such as limited budgets, resources, and technology should be considered to select the accessibility indicators. In this case, a linear model of accessibility index may be preferable due to its simplicity. Based on those considerations, the overall conceptual design in developing the accessibility model (RNAI) is as follows:

1) There is a need to integrate road project appraisal with the measurement of accessibility, e.g., using the infrastructure-based accessibility model. As this research focuses on how to manage accessibility through road infrastructure, the strategy, action plan and budget allocation for regional accessibility management can only be synchronised if there is a tool or model to integrate accessibility features with a road asset management tool like the HDM-4. In this case, the model needs to explicitly include road infrastructure features associated with road appraisal attributes, e.g. length of the road network and its performance indicators, as the main component of measurement. Once it is integrated, the accessibility model may then be added as a decision criterion in the appraisal of road asset management to ensure the target of accessibility will be precisely interpreted into a technical term of road asset management. Thus, the components of the accessibility measure should be based on road infrastructure features.
2) There is a need to include road performance as an accessibility component, in addition to road density. Currently, the most popular measurement of road infrastructure-based accessibility is road density, which was developed by the World Bank (Day and Ellis, 2014; Berg et al., 2018). It is felt, however, that the measurement of accessibility, which only relies on road density, may be biased. A higher level of road network accessibility should not only be dictated by the network length within an area but also by its performance. Based on the

concept of road density, the denser the road network is in a geographical area, the better the level of accessibility. However, if the roads are mostly in poor condition, the performance cannot satisfy the minimum standards of service, such as travel speed and riding comfort. Thus, in the measurement of accessibility, a road network that is in poor condition must be reflected and indicated by a lower level of accessibility index.

3) There is a need to consider the "reliability of road access" throughout the year. Due to the recent issue of climate change, the road infrastructure needs to be less susceptible to weather exposure (see **Chapter 4**). It means that the road network should be reliable enough to provide access to road users for the whole year. Based on a road engineering approach, the level of accessibility in a road network which has sealed pavements is more reliable than an unsealed network of road pavement. In unsealed road networks, the roads may become inaccessible or even closed because of worsening road conditions during the rainy season (Sohn, 2006; Kaspersen and Halsnæs, 2017). It was claimed that the use of sealed roads is more reliable to ensure they remain open and in service throughout the year (Borowska-Stefańska and Wiśniewski, 2018). Accordingly, road networks that are more sensitive to climate exposure, e.g. consisting of gravel or earth roads, should also be associated with a lower level of accessibility.
4) There is a need to minimise disparity in accessibility levels between geographic areas, and to reduce the degree of segregation between areas and promote regional development by using the concept of equity. In the context of the RNAI, Rock et al. (2014) pointed out that equity may be realised by setting up minimum standards for accessibility. However, in practice, variance in the levels of accessibility are inevitable. Equity cannot be achieved by treating all people equally; instead, it can be achieved by equitably treating all people as per their circumstances (Hay and Trinder, 1991; Geurs et al., 2016). Therefore, an optimum level

of accessibility can be achieved once it meets minimum standards of a national accessibility index, and the gap between areas is not significant.

5.4 Step 2: Selection of Indicators

In general, there are some technical indicators of road appraisal that may be linked with accessibility. However, the selection of indicators needs to fit the conceptual design and the requirement of the RNAI model to accommodate the attributes of climate and road infrastructure. As the conventional road appraisal already considers traffic in its economic assessment, to anticipate double counting, the accessibility model should exclude traffic-related indicators from the measurement, e.g., traffic density (volume per capacity ratio). Based on the theoretical framework of the RNAI model, there are three essential requirements of accessibility features, i.e. availability of connection by road networks, the performance of road networks, and the reliability of road access throughout the year. In road asset management, this requirement may be satisfied through three components, i.e. network length, condition of the road network and the type of pavement used on the road network (see **Figure 5.3**).

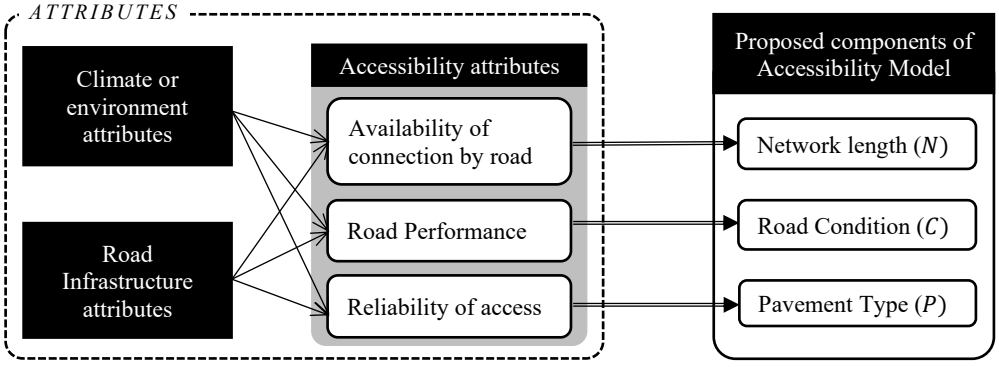


Figure 5.3 Components of the RNAI model

The indicators need to be assessed to identify the data characteristics to ensure the sustainability of the model in developing countries. The characteristics include the availability of data, the quality of data to measure accessibility, the cost of data collection, the technology used for

measuring the data, and the information quality level of data (Amrozi and Evdorides, 2019). The general assessment regarding the characteristics of the alternative accessibility indicators is shown in **Table 5.1**.

Table 5.1 Data characteristics of accessibility indicators

Accessibility		Characteristic of data*					Comment
Component	Alternative indicators	Availability	Quality	Cost	Technology	IQL	
Network length	▪ Road density	+	+	+	+	IV	Promising
	▪ Length of road	+	+	+	+	II	Promising
	▪ Number of lanes	+	0	+	+	II	Related to traffic
Condition	▪ Road condition (good, fair)	+	+	+	+	IV	Promising
	▪ Roughness	0	+	+	0	II	Promising
	▪ Surface distress index (visual)	+	+	+	+	II	Promising
Pavement	▪ Type of pavement	+	+	+	+	IV	Promising
	▪ Pavement strength	-	+	-	-	I	Too detailed

** (+): good or suitable; (-): poor or unsuitable; (0): neither good nor poor, n/a.*
IQL = Information quality level, I = the most detail; IV = the most general.
Availability: the availability of data and the ability of a user to access the information or resource. The
Quality: the ability of data set to serve an intended purpose. the more trusted and reliable the data the more preferred.
Cost: cost of labour, material, and other cost elements which may incurred to get the data.
Technology: the utilization of tools, gadget, procedure, storage to collect, secure and process the data
IQL: The Information Quality Level. The more general type of data is preferred for simplification and ease of interpretation.

As the accessibility model links communication between road authorities and stakeholders, who may not be experts in road engineering, (see **Chapter 3.4.3**), the indicators should have excellent data characteristics which satisfy those of developing countries. Also, they should be simple and less technical, e.g. using macro-level data of road asset management, i.e. IQL-IV (Robinson et al., 1998). Thus, road density, road condition, and type of pavement was preferred as the component of the accessibility model. In practice, an accessible or drivable road that is represented by a good and fair road condition may be defined based on roughness (IRI), or the surface distress index (SDI) following standards from the road authority. It means that road managers still use the more detailed data such as 'roughness' instead of 'good and fair road condition' as an input to feed a road appraisal tool such as the HDM-4 and calculate the accessibility index. How the components of the RNAI model link with the HDM-4 as a road

appraisal tool are shown in **Table 5.2**. The assessment of the strengths and weaknesses of the selected indicators is in **Table 5.3**.

Table 5.2 RNAI components and the link to the HDM-4 as a road appraisal tool

Component	Consideration of equity in the accessibility model			Link to HDM-4 software
	Requirement	Indicator	Quantification	
Network length (N)	Each region should have enough road network connections to reach all locations in need of transport services	Length of the road network within an area	Length of road network per land area (total road density)	Length of the road network
Condition (C)	Each region should have an adequate percentage of accessible road	A passable road which satisfies the minimum level of service, e.g., travel speed and riding comfort	Percentage or ratio of the road in a good or fair condition (based on predefined standards)	Roughness (IRI, m/km)
Pavement type (P)	Each region should have a satisfactory percentage of reliable road access (ensuring the road is always open throughout the year)	A*ll-weather* type of road pavement, i.e., road surface which may withstand climate exposure	Percentage or ratio of the sealed road surface, e.g., asphalt or concrete	Type of Pavement

Table 5.3 The strengths and weaknesses of selected accessibility indicators

Accessibility		Assessment	
Component	unit	strengths	weakness
Road density	km per sq.km area	Popular and widely used in the accessibility measurement	Ignore the capacity of the road
Good and fair road condition	km	Link to roughness and HDM-4 features	The standards may vary
Sealed road	km	Clear and easy to understand	Does not reflect the actual strength of roads

5.5 Step 3: Data Treatment

It is necessary to provide a complete and good quality of data to develop a robust composite indicator. However, outliers and missing values can occur in any data set (Ott and Longnecker, 2015). Therefore, it is important to check the availability and quality of data before doing further computation and analysis.

5.5.1 Missing Values

Different approaches and considerations should be used for examining missing values of a dataset as they may become unintended benchmarks (Nardo et al., 2008). In general, there is no best method to deal with missing data. Before any data treatment, it is essential to understand the reason why the data is missing. Once it is confirmed, according to Lawson et al. (2008) the missing value may be addressed using the following methods: (1) deletion, omits the missing data from the analysis; (2) single imputation, try to input the missing data using mean, median or regression computation; (3) multiple imputation, e.g. Markov Chain Monte Carlo algorithm.

5.5.2 Data Outliers

In the statistical perspective, an outlier is defined as a data point that differs significantly from other values or data that lies outside the overall pattern of data distribution (Ott and Longnecker, 2015). By using a box plot diagram, the data may be identified as an outlier when plotted outside the whisker (Field, 2017). Once identified, outliers are often excluded from the dataset because they may indicate experimental errors due to variability in measurements that can cause severe problems in further statistical analysis (Munda and Nardo, 2005).

5.6 Step 4: Multivariate Analysis

The multivariate analysis aims to assess the statistical and conceptual coherence in the structure of the dataset (Nardo et al., 2008). An accessibility component may have complex and unknown relationships with other components. Therefore, it is necessary to discover the correlation between accessibility components using a statistical analysis like Pearson's correlation to avoid double-counting. The value of Pearson's correlation ranges from zero to one. Zero value means that two variables are completely different, while a value closer to one means that the indicators are similar or identical. The correlation between the RNAI components is elaborated using the dataset from Indonesia (see **Chapter 6.2.3**).

5.7 Step 5: Normalisation

Being developed using a composite indicators method, the RNAI will have several indicators which potentially result in a different unit of measurement. However, to aggregate some indicators into a single index, it is necessary to express all the indicators into the same range and standard unit of measurements (Nardo et al., 2008). If this is not possible, the indicators can be transformed into a pure dimensionless number through a normalisation procedure.

There are several normalisation methods used to develop composite indicators (Nardo et al., 2008). However, as each method has its strengths and weaknesses (see **Table 5.4**), the selection of the normalisation method should respect both the theoretical framework and data properties (Field, 2017). In this accessibility model, the distance to a reference point is implemented as the normalisation method because the method is precise, less subjective (suitable to the concept of equity), easy to understand, and satisfies both the theoretical framework and data properties.

Table 5.4 Assessment of normalisation methods for the RNAI model

Method	Equation	Strengths	Weaknesses	Comment
Ranking	Ascending or descending order $I_{qc}^{t} = Rank\left(x_{qc}^{t}\right)$ Range: 1 to unlimited	▪ Simple ▪ Not affected by outlier	Omit (lost) information	Not suitable due to information loss
Z-score *(Standardization)*	The data minus mean then divided by the standard deviation $I_{qc}^{t} = \frac{x_{qc}^{t} - x_{qc=\bar{c}}^{t}}{\sigma_{qc=\bar{c}}^{t}}$ Range: -3 SD to +3 SD, zero equal to the mean	▪ Taking account both the mean and variability of raw score ▪ Can compare two scores from different distributions characteristics	▪ Confuse applicants, lost meaning on the raw score ▪ Extreme values may be an outlier	Not suitable due to extreme value
Min-Max *(re-scaling)*	$I_{qc}^{t} = \frac{x_{qc}^{t} - min_{c}\left(x_{q}^{t_0}\right)}{max_{c}\left(x_{q}^{t_0}\right) - min_{c}\left(x_{q}^{t_0}\right)}$ Range: 0 to 1	▪ Identical range [0-1] ▪ Can widen the range of small indicator interval	Min-max could be outliers which can distort the index	Not suitable due to extreme value and information loss
Distance to a reference point (cut-off) as a benchmark	▪ Leader/maximum ▪ Mean, median ▪ Set/target value $I_{qc}^{t} = \frac{x_{qc}^{t}}{x_{qc=\bar{c}}^{t_0}}$ or $I_{qc}^{t} = \frac{x_{qc}^{t} - x_{qc=\bar{c}}^{t_0}}{x_{qc=\bar{c}}^{t_0}}$	▪ Clear ▪ Benchmarking ▪ Less subjective	Leader/maximum/extreme values could be outliers	Promising by using maximum or mean (average) as a benchmark (fits the concept of equity)
Categorical scale ▪ Stars rating. ▪ natural break ▪ qualitative: good, poor	Assigns a score for each indicator and categories based on percentiles of indicator's distribution	▪ Flexible ▪ Easy	Exclude information about variance of transformed indicator	Promising because it is widely used and easy to understand

Source: Freudenberg (2003); Nardo et al. (2008); Rumsey (2010); Mazziotta and Pareto (2013)

5.7.1 The Base Form of Accessibility Components

Based on the selection indicators assessment in **Chapter 5.4**, the chosen indicators for the accessibility components are network length, road conditions, and type of road pavement. The base form of measurement for those components are the length of road with predefined attributes. However, in the application, those components are quantified using popular indicators in road asset management or infrastructure-based accessibility measurement to satisfy the concept of equity and the practical aspect of the accessibility model (see **Table 5.5**).

Table 5.5 Individual form of accessibility components

Accessibility		[Type 0] Base form ($x = 0$)	Alternative form (x)	
Component	Code		[Type A] a popular form in road asset management indicator ($x = A$)	[Type B] A popular form in infrastructure-based accessibility measurement, i.e. road density ($x = B$)
Network length	(N_x)	Length of the total road network	Road density	Road density of total road length
Condition	(C_x)	Length of the road in a good or fair (steady-state) condition	Ratio of road in a good or fair condition	Road density of good and fair conditioned roads
Pavement	(P_x)	Length of sealed or paved road surface	Ratio of sealed or paved road surface	Road density of sealed or paved road surface

In terms of the form of accessibility components, type zero (Type 0) data is the raw data of the measurement without adjustment. The measured data can be inferred as the base form of data or a parameter of the RNAI component, i.e. length of the entire road network (N), length of roads in good and fair (steady-state) condition (C), length of sealed or paved road surface (P). Meanwhile, in the form of Type A and Type B, the component has been adjusted to match the form of recent popular indicators in road asset management (Type A), and in road unfractured-based accessibility measurements like road density (Type B). The adjusted form of raw data becomes Type A, and Type B is intended to satisfy the concept of equity and the practical aspect of the accessibility model.

Alternative A: In the form of a popular indicator in road asset management.

$$N_A = R_d = \frac{L_{tn}}{S} = \frac{length\ of\ total\ road\ network}{land\ area}\frac{[km]}{[km^2]}; range[0-\infty]$$

$$C_A = \frac{L_{gf}}{L_{tn}} = \frac{length\ of\ good\ and\ fair\ road\ condition}{length\ of\ total\ road\ network}\frac{[km]}{[km]}; range[0-1]$$

$$P_A = \frac{L_{ac}}{L_{tn}} = \frac{lengthofsealedroadsurface(asphalt, cement)}{length\ of\ total\ road\ network}\frac{[km]}{[km]}; range[0-1]$$

Alternative B: In the form of a popular indicator in infrastructure-based accessibility measurement, i.e. road density.

$$N_B = \text{totallength} = \frac{L_{tn}}{S}\frac{[km]}{\left[km^2\right]}; range[0-\infty]$$

$$C_B = goodandfairroadcondition = \frac{L_{gf}}{S}\frac{[km]}{\left[km^2\right]}; range[0-\infty]$$

$$P_B = sealedroadsurface(asphalt, cement) = \frac{L_{ac}}{S}\frac{[km]}{\left[km^2\right]}; range[0-\infty]$$

Where N_x= network length (availability of road asset) for form x; C_x= condition of road asset for form x; and P_x = Pavement type for form x; x= alternative form; R_d= road density; L_{tn}= length of total road network; S = land area; L_{gf} = length roads in good and fair condition; L_{ac}= length of sealed road surface (asphalt, cement).

5.7.2 Normalisation Technique

The main objective of the normalisation procedure is to bring all the components of accessibility into the same unit analysis and value range. For achieving this, the base form of the RNAI components are normalised using three normalisation types or techniques, as shown in **Table 5.6** and are elaborated on in more detail in the following subsection.

Table 5.6 Technique to normalize the RNAI component

Component		Normalisation type or technique		
		Type-1	Type-2	Type-3
Individual form		A	B	B
Normalising technique*	Unit of measurement	N divided by the maximum value	N, C, and P divided by the maximum value	N, C, and P divided by the average value
	Threshold	Maximum N equal to one	Maximum N, C and P equal to one	Maximum N, C and P equal to T

5.7.2.1 Normalisation Type-1

As the component of condition (C) and pavement (P) already have a dimensionless unit of measurement and the same range of value [0-1], the component of network length (N) must be expressed in the same characteristics. The value of road density (R_d) is divided by the maximum value of national road density ($R_{d\ max}$) and the outliers are excluded from the dataset (see **Table 5.6**). Also, extreme values could be outliers (weaknesses of distance to a reference point method). Therefore, a maximum threshold value equal to one is set to remove the effect of extreme values (outliers) from the model and ensure the range of the network length component (N) is between zero and one [0-1]. Removing the effect of outliers is vital because they are an extreme values that are rarely found, but can lead to errors in the overall model and results (Huber, 2011).

$$N1 = min\left\{1, \quad \frac{N}{N_{max}}\right\} = min\left\{1, \frac{(L_{tn}/S)}{(L_{tn}/S)max}\right\} \frac{[km]/[km^2]}{[km]/[km^2]}; range[0-1]$$

$$C1 = C, and P1 = P; range[0-1]$$

5.7.2.2 Normalisation Type-2

As an alternative method, the C and P component may be normalised using the same denominator with $N1$, i.e. divided the road length component by land area (road density) to get the same unit of measurement. Then by dividing the values by the maximum value (from the national dataset) to ensure the outcome is always between zero and one [0-1]. Furthermore, following the $N1$ normalisation technique to remove the effect of extreme values (outliers), maximum threshold values equal to one are applied.

Normalising $C2$ and $P2$ by dividing the component by its maximum national value:

$$C2 = \frac{L_{gf}/S}{(L_{gf}/S)_{max}} = \frac{\frac{length\ of\ good\ and\ fair\ road\ condition}{land\ area}}{\left(\frac{length\ of\ good\ and\ fair\ road\ condition}{land\ area}\right)max} \frac{\frac{[km]}{[km^2]}}{\frac{[km]}{[km^2]}}; range[0-\infty]$$

$$P2 = \frac{L_{ac}/S}{(L_{ac}/S)_{max}} = \frac{\frac{length\ of\ sealed\ road}{land\ area}}{\left(\frac{length\ of\ sealed\ road}{land\ area}\right)max} \frac{\frac{[km]}{[km^2]}}{\frac{[km]}{[km^2]}}; range[0-\infty]$$

Applying a threshold (maximum =1) to remove the effect of outliers and ensure the range of the index is always between zero and one [0-1]:

$$N2 = min\left\{1, \quad \frac{(L_{tn}/S)}{(L_{tn}/S)_{max}}\right\} \frac{[km]/[km^2]}{[km]/[km^2]}; range[0-1]$$

$$C2 = min\left\{1, \quad \frac{(L_{gf}/S)}{(L_{gf}/S)_{max}}\right\} \frac{[km]/[km^2]}{[km]/[km^2]}; range[0-1]$$

$$P2 = min\left\{1, \quad \frac{(L_{ac}/S)}{(L_{ac}/S)_{max}}\right\} \frac{[km]/[km^2]}{[km]/[km^2]}; range[0-1]$$

5.7.2.3 Normalisation Type-3

Using the same procedure and consideration, the technique to use maximum values may be substituted using the average value from the dataset. However, to ensure the value range [0-1] the threshold value should be adjusted following the maximum and average value which is denoted as $T = X_{max}/X_{mean}$.

$$N3 = min\left\{T_N, \quad \frac{(L_{tn}/S)}{(L_{tn}/S)_{mean}}\right\} \frac{[km]/[km^2]}{[km]/[km^2]}; range[0-T_N]$$

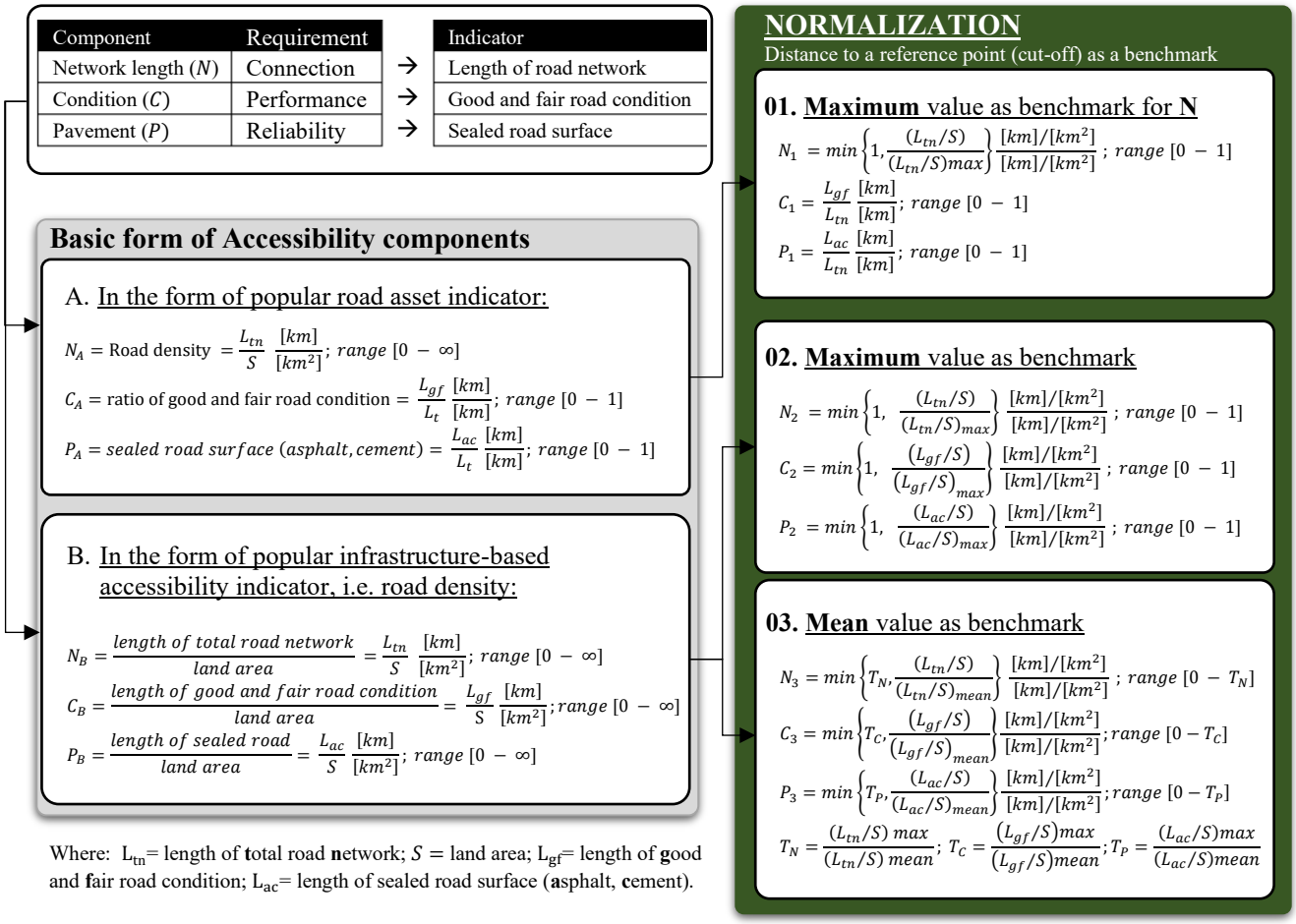
$$C3 = min\left\{T_C, \quad \frac{(L_{gf}/S)}{(L_{gf}/S)_{mean}}\right\} \frac{[km]/[km^2]}{[km]/[km^2]}; range\ [0-T_C]$$

$$P3 = min\left\{T_P, \quad \frac{(L_{ac}/S)}{(L_{ac}/S)_{mean}}\right\} \frac{[km]/[km^2]}{[km]/[km^2]}; range\ [0-T_P]$$

$$T_N = \frac{(L_{tn}/S)\ max}{(L_{tn}/S)\ mean};\ T_C = \frac{(L_{gf}/S)max}{(L_{gf}/S)mean};\ T_P = \frac{(L_{ac}/S)max}{(L_{ac}/S)mean}$$

Where T_X = threshold for component x; $x = N$, C and P.

The resume of the normalisation technique for developing accessibility model (the RNAI) is shown in **Figure 5.4**.



Where: L_{tn}= length of **t**otal road **n**etwork; S = land area; L_{gf}= length of **g**ood and **f**air road condition; L_{ac}= length of sealed road surface (**a**sphalt, **c**ement).

Figure 5.4 Normalization of accessibility components

5.8 Step 6: Weighting and Aggregation

The weighting parameter reflects how important and significant the effect of each parameter is on the overall result (Rumsey, 2007). In this research, since the RNAI is developed based on the concept of equity, the ideal method should be the equal weighting method. The method is simple and not affected by outliers (see **Table 5.7**). In terms of aggregation, the RNAI model was inspired by the recent models of accessibility, such as the Rural Accessibility Index (RAI) and Accessibility/Remoteness Index of Australia (ARIA) which measure accessibility using a linear model. The model summarises the value of each accessibility component into a single score or index (see **Chapter 2**). A linear model was preferred for the aggregation technique

because it offers clear and straightforward calculations that seem more applicable to be implemented in developing countries. The general form of the RNAI model is shown in **Equation 5.1**.

Table 5.7 Assessment of several weighting methods for the RNAI model

Weighting method	Strengths	Weaknesses	Comment
Equal Weight	▪ Simple ▪ Not affected by outlier	Not consider the level of impact and priority for each indicator	Promising, suitable for the concept of equity
Based on a statistical model ▪ Regression analysis ▪ Principal components analysis	Objective	Data reliability	Les suitable because complicated and the data in a developing country often not ideal and unreliable
Based on subjective opinion (e.g., public, expert, government) ▪ Analytic Hierarchy Process ▪ Conjoint analysis	Consider public opinion	Subjective, political spoil	Les suitable because it is subjective and prone to political spoil, but it may be accommodated in the multi-criteria analysis.

The basic equation of the RNAI model:

$$M_i = \frac{\alpha\ N_i + \beta\ C_i + \gamma\ P_i}{\alpha + \beta + \gamma}; range[0-1] \qquad \text{Equation 5.1}$$

where: M_i = accessibility model using normalisation type i; N_i = Component N of accessibility model for normalisation type$-i$; $i \in 1, 2, 3$; α, β and γ are weighting factor.

Subsequently, as the weighting uses an equal weight method to meet the concept of equity ($\alpha + \beta + \gamma = 1$), the equation becomes:

$$M_i = \frac{1}{3} \times (N_i + C_i + P_i) \qquad \text{Equation 5.2}$$

Following the three alternative types of normalisation, as described in **Chapter 5.7**, the RNAI model may then be transformed into three alternative formulas:

$$M_1 = \frac{1}{3} \times \left(min\left\{1, \frac{(L_{tn}/S)}{(L_{tn}/S)_{max}}\right\} + \frac{L_{gf}}{L_{tn}} + \frac{L_{ac}}{L_{tn}} \right); \text{range [0-1]} \qquad \text{Equation 5.3}$$

$$M_2 = \frac{1}{3} \times \left(min\left\{1, \frac{(L_{tn}/S)}{(L_{tn}/S)_{max}}\right\} + min\left\{1, \frac{(L_{gf}/S)}{(L_{gf}/S)_{max}}\right\} + min\left\{1, \frac{(L_{ac}/S)}{(L_{ac}/S)_{max}}\right\} \right); \text{range [0-1]} \qquad \text{Equation 5.4}$$

$$M_3 = \frac{\left(min\left\{T_N, \frac{(L_{tn}/S)}{(L_{tn}/S)_{mean}}\right\} + min\left\{T_C, \frac{(L_{gf}/S)}{(L_{gf}/S)_{mean}}\right\} + min\left\{T_P, \frac{(L_{ac}/S)}{(L_{ac}/S)_{mean}}\right\}\right)}{T_N + T_C + T_P} \text{ ; range [0-1]} \qquad \text{Equation 5.5}$$

where: $M_i =$ accessibility model type $i; i \in 1, 2, 3$; T_N = threshold for component N; T_C = threshold for component C; T_P = threshold for component P.

Accessibility Index relative to international benchmark

As an alternative standpoint, the accessibility index may also be transformed or measured relative to a particular country as an international benchmark or standard to give a fair comparison of accessibility levels between countries. This transformation may use a calibration factor by adopting a popular formula in the theoretical exchange rate, e.g. Purchasing Power Parity (PPP) from the World Bank (see **Equation 5.6**). The PPP formula tries to equalise the local characteristics and level of acceptance levels in different countries by referring to the same standards or values as the benchmark (Lafrance and Schembri, 2002). The calculation procedure for the calibration is dividing the cost of a particular good in country X in currency X by the cost of the same good in country Y in currency Y, e.g. USD as the benchmark. This analogy can then be applied to measure an international accessibility index, i.e. an accessibility index relative to a specific country as a benchmark.

In practice, the range of values and interpretation for the component C and P in the RNAI model should be theoretically consistent if engineering standards are followed. However, component N (road density) may vary because of the level of road density in a developed country like the United Kingdom may be three or fourth times higher than a developing country such as Indonesia. As a consequence, the component of road density (N) in a particular country (e.g. country x) need to be adjusted relative to an international benchmark (z) using a calibration factor (θ_{zx}), as shown in the following equations.

Purchasing Power Parity (PPP) formula from the World Bank:

$$Purchasingpowerparity(PPP) = \frac{Cost\ of\ good\ in\ currency\ X}{Cost\ of\ good\ in\ US\ dollar} \quad \text{Equation 5.6}$$

By substituting 'cost' with 'road density', the calibration factor for measuring accessibility may become:

$$Calibratingfactorforcountyxrelativetoz(\theta_{ZX}) = \frac{road\ density\ in\ country\ X}{road\ density\ in\ country\ Z} \quad \text{Equation 5.7}$$

therefore, the accessibility formula (see **Equation 5.2**) becomes:

$MG_1 = \frac{1}{3} \times (\theta_Z N_1 + C_1 + P_1)$, for normalisation type-1 Equation 5.8

$MG_2 = MG_3 = \theta_Z M_x$, for normalization type-2 and type-3 Equation 5.9

Where MG_i= Model global relative to international benchmark; θ_{ZX}= calibrating factor of accessibility for country X relative to country Z as the international benchmark, $M_i =$ accessibility model type-i; $i \in 1, 2, 3$.

5.9 Interpretation and Visualisation of the Accessibility Index (RNAI)

5.9.1 Interpretation of the RNAI

The outcome for the RNAI quantification is called an accessibility index. However, as the indexing scheme is hard for ordinary people to interpret the meaning, the index can be converted into a more straightforward measurement unit, such as a star rating. For creating the associated rating, the values are categorised into five equal scales known as the five-star rating system. A one-star rating represents the lowest level of accessibility, e.g. very remote or isolated, while a five-star rating represents the best accessibility. The meaning and interpretation of the RNAI values and ratings are shown in **Table 5.8**.

Table 5.8 The RNAI value and meaning

Accessibility (RNAI)			Meaning	
Index	Rating	Level		
> 0.8 – 1.0	5	Very High (excellent)	*Unrestricted access*	to a wide range of services and opportunities for social-economic interaction. The area has several route options. Road surfaces are mostly sealed and always reliable throughout the year.
>0.6 – 0.8	4	High (good)	*Relatively unrestricted access*	to a wide range of services and opportunities. The area has some route options. Road surfaces are mostly sealed and reliable throughout the year.
>0.4 – 0.6	3	Moderate (average)	*Some restrictions of access*	to a wide range of services and opportunities. The area has route options. Road surface is partly unsealed, but access is still reliable for vehicles throughout the year.
>0.2 – 0.4	2	Low (remote)	*Significantly restrictions of access*	to a wide range of services and opportunities. The area has limited route options. Road surface is partly unsealed and may not be reliable throughout the year.
0.0 – 2.0	1	Very Low (isolated)	*Very restricted access*	to reach services and opportunities. The area typically does not have different route options. Road surface is mostly unsealed and unreliable throughout the year.

5.9.2 Visualisation of the RNAI

The unit analysis of RNAI is a geographical area, either based on administrative, geospatial, or artificial boundaries. To present the dynamical value of RNAI between areas, besides using mathematical indices (index and star rating), a pictorial technique presentation such as graph and geospatial information system (map) can be added. A graphical presentation can be produced using *Microsoft Excel*. At the same time, an isochronal map can be generated using geographic information systems (GIS) software such as *ArcGIS, MapInfo, Base, Geosoft, gisAMPS* and *QGIS*. In this study, the isochronal map presentation does not require a complex GIS analysis. It only used to show the RNAI value. Software that is designed for developing countries, simple, and low-cost is preferable. Therefore, the *QGIS software* is favoured because it is free, user-friendly, and can be installed on Windows, Mac, Linux, BSD and Android. The *QGIS software* can be downloaded free of charge from the QGIS website, http://www.qgis.org. The *QGIS software* interface and an example of the RNAI presentation are shown in **Figure 5.5** while the procedures for generating an isochronal map of RNAI value in QGIS are shown

in **Appendix C**. By using map presentation, it is easier to identify accessibility levels across the country and make comparisons. For example, as shown in **Figure 5.5**, Kalimantan Tengah (code 21) has an orange colour indicating that the region has a low level of accessibility. In contrast, Jawa Tengah (code 14) has a light green colour indicating that the region has a high level of accessibility across the province.

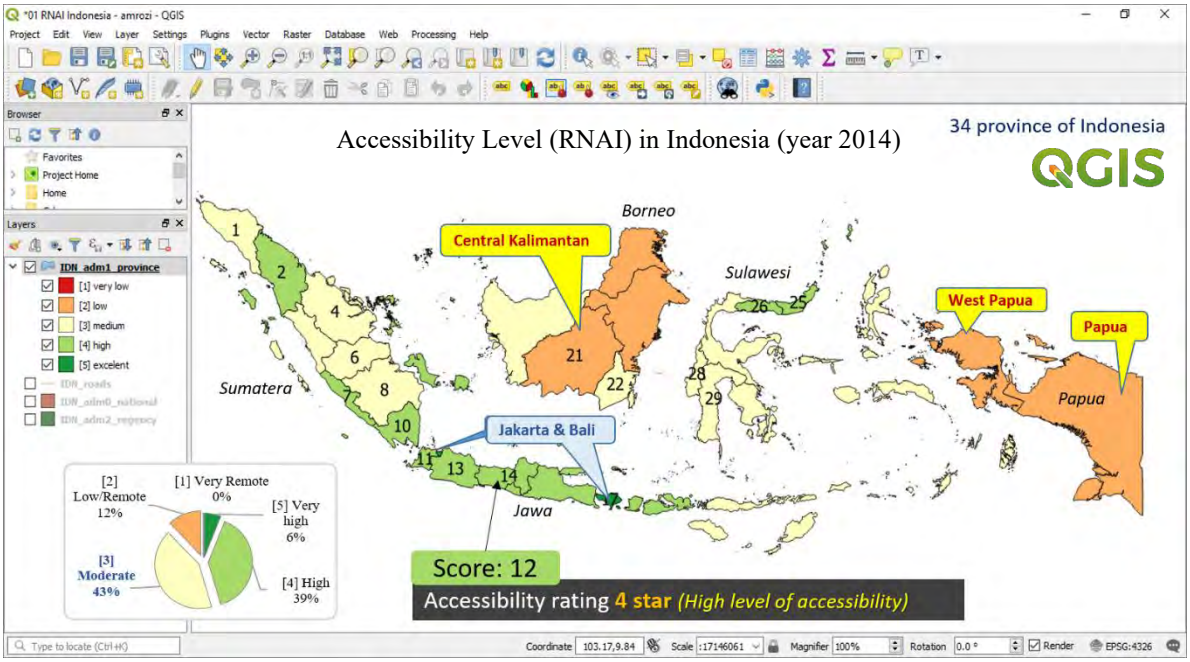


Figure 5.5 Interface of QGIS software

5.10 Summary

The Road Network Accessibility Index (RNAI) is a linear model of accessibility that focuses on road infrastructure and its condition. The model was constructed following the composite indicator method and developed using the concept of equity. Based on the result of the model development procedure, three alternative models may be used to quantify the RNAI value, named model M_1, M_2 and M_3. These models are explained in **Table 5.9**.

Table 5.9 Comparison of alternative models to quantify the RNAI

Differentiator	Alternative model of accessibility measurement		
	M_1	M_2	M_3
Base form	a popular form in road asset management indicators:	a popular form in the measurement of infrastructure-based accessibility, i.e. road density:	
Normalisation	Uses the maximum value from the national data as a benchmark to normalise component N only	Uses the maximum value from the national data as a benchmark to normalise component N, C and P	Uses the mean value of the national data as a benchmark to normalise component N, C and P
Formula [a]	$M_1 = \frac{1}{3} \times \left(min\left\{1, \frac{(L_{tn}/S)}{(L_{tn}/S)_{max}}\right\} + \frac{L_{gf}}{L_{tn}} + \frac{L_{ac}}{L_{tn}} \right)$	$M_2 = \frac{1}{3} \times \left(min\left\{1, \frac{(L_{tn}/S)}{(L_{tn}/S)_{max}}\right\} + min\left\{1, \frac{(L_{gf}/S)}{(L_{gf}/S)_{max}}\right\} + min\left\{1, \frac{(L_{ac}/S)}{(L_{ac}/S)_{max}}\right\} \right)$	$M_3 = \frac{1}{T_N + T_C + T_P} \times \left(min\left\{T_N, \frac{(L_{tn}/S)}{(L_{tn}/S)_{mean}}\right\} + min\left\{T_C, \frac{(L_{gf}/S)}{(L_{gf}/S)_{mean}}\right\} + min\left\{T_P, \frac{(L_{ac}/S)}{(L_{ac}/S)_{mean}}\right\} \right)$

a. Where: M_i = model i; $i \in 1, 2, 3$; N = network length; C = condition of road network; P = Pavement type; L_{tn} = length of total road network; S = land area; L_{gf} = length of roads in a good and fair condition; L_{ac} = length of sealed road surface; T_N = threshold for component N; T_C = threshold for component C; T_P = threshold for component P

In general, those models have the same components of measurement, i.e. network length (N), road condition (C) and pavement type (P). The critical difference lies in the base form of accessibility components and the normalization procedure to quantify the accessibility level. In terms of the base form of accessibility components, as illustrated in **Table 5.9**, model M_1 uses a popular form of indicator in road asset management, i.e. road density (N), ratio of good or fair condition of road (C), and ratio of sealed (paved) road surface (P) while model M_2 and M_3 uses road density (a popular indicator in recent infrastructure-based accessibility measurement) which is distinguished by three accessibility attributes, i.e. road density of total road length (N), road density of good or fair condition road (C), and road density of sealed (paved) road surface (P). In terms of the normalisation technique, Model M_1 and M_2 uses the maximum value of national data as a reference point (cut-off) to normalise the components of accessibility index. The difference in the model M_2 is that it uses the max value to normalise all the three components (N, C, P) but M_1 normalises the N component only. Meanwhile, M_3 uses a mean

value of national data to normalise all the three components (N, C, P). Consequently, as the base form and normalisation procedure are different, the formula to quantify the accessibility index is slightly different (see **Chapter 5.8**). Apart from these three accessibility models, as an alternative for comparing the accessibility index head to head between countries, the indexes may also be transformed into a global accessibility index or accessibility index relative to an international benchmark (MG_i) using a calibration factor (θ_{ZX}).

Overall, all the models are theoretically relevant to the concept of equity and accessibility measures which focus on road asset management features. Nevertheless, the models still need to be tested using Indonesia as a case study to ensure their robustness in the presence of uncertain combinations of input variables. The corresponding tests are presented and elaborated in more detail in **Chapter 6** and **Chapter 7**.

CHAPTER 6

MODEL TESTING

6.1 Introduction

This chapter presents how the accessibility models developed in **Chapter 5** can be tested and evaluated using real datasets to test the robustness of the models and select the best model that meets the theoretical and technical concept of accessibility measurement. The robustness test aims to identify all possible sources of uncertainty in the development, normalisation and aggregation method, such as missing values and outliers. This robustness test is critical to ensure that the model is valid for any possible combination of inputs and provide an accurate picture of the perceived level of accessibility.

This chapter consists of five sections. First, it presents the statistical properties of data and how the alternative models may be applied in practice, i.e. using the Indonesian state as the source of data to test the theoretical concept of the RNAI model. The subsequent sections elaborate on the fitness of alternative models by testing the robustness of the model to the uncertainty in the combination of input variables and how the model forms behave. An alternative form of accessibility measurement, i.e. accessibility relative to an international benchmark, is presented to compare the accessibility level between countries.

6.2 Application of the RNAI Model in Indonesia

As previously mentioned in **Chapter 3**, the RNAI model was developed using Indonesia as a case study to represent the characteristics of developing countries. All the data needed to measure the RNAI in Indonesia are published annually by the road authorities and can be accessed through the Statistics Indonesia (BPS) website.

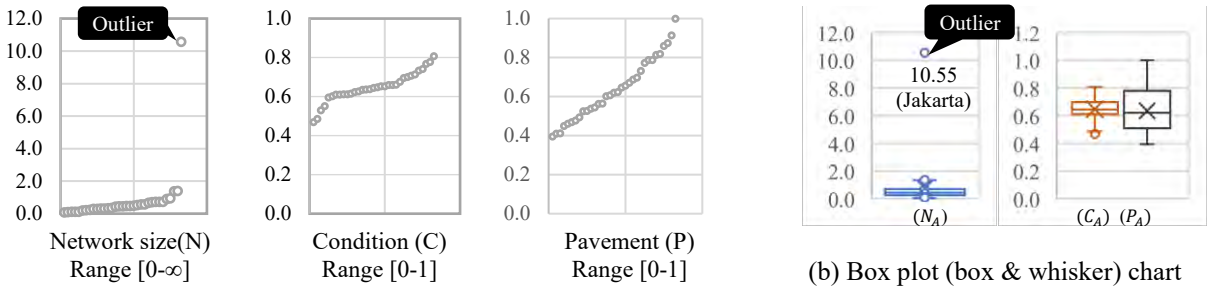
6.2.1 Defining the Unit of Analysis

As this research addresses the condition and distribution of accessibility across a country, the unit of analysis of the RNAI should be based on provincial area, one unit below country.

6.2.2 Data Characteristic

6.2.2.1 Missing data and outliers

Based on the Indonesian dataset for 2014, there was no missing value identified. All required data for measuring the RNAI model was available in the form of road length by pavement type, road condition and asset ownership. In the case of data outliers, the outliers can be identified by assessing the distribution pattern of data, e.g. using a scatter plot or box plot diagram (Coles et al., 2001; Santoso, 2017). The distribution of accessibility components by the province in Indonesia for 2014 are shown in **Figure 6.1**.



(a) Ascending value of accessibility component

(b) Box plot (box & whisker) chart of accessibility component

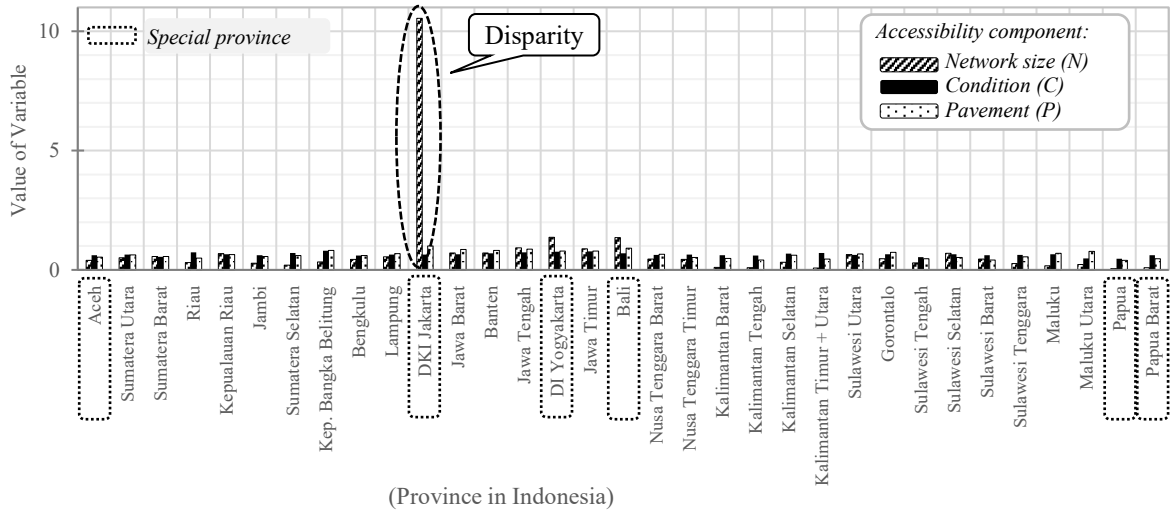
Note: based on The national distribution of accessibility components by province in Indonesia in the year 2014

Figure 6.1 Identification of data outliers

As illustrated in the scatter plot of accessibility components in **Figure 6.1a**, the extreme value of road density was DKI Jakarta which identified as an outlier. This value reflects a high gap in road density between DKI Jakarta and other provinces in Indonesia. Although a higher value of road density had been anticipated because Jakarta is the capital, the gap was not expected to be ten times the average value of road density in Indonesia. This outlier identification was also confirmed through the box plot diagram (see **Figure 6.1b**). The value of road density (N) for

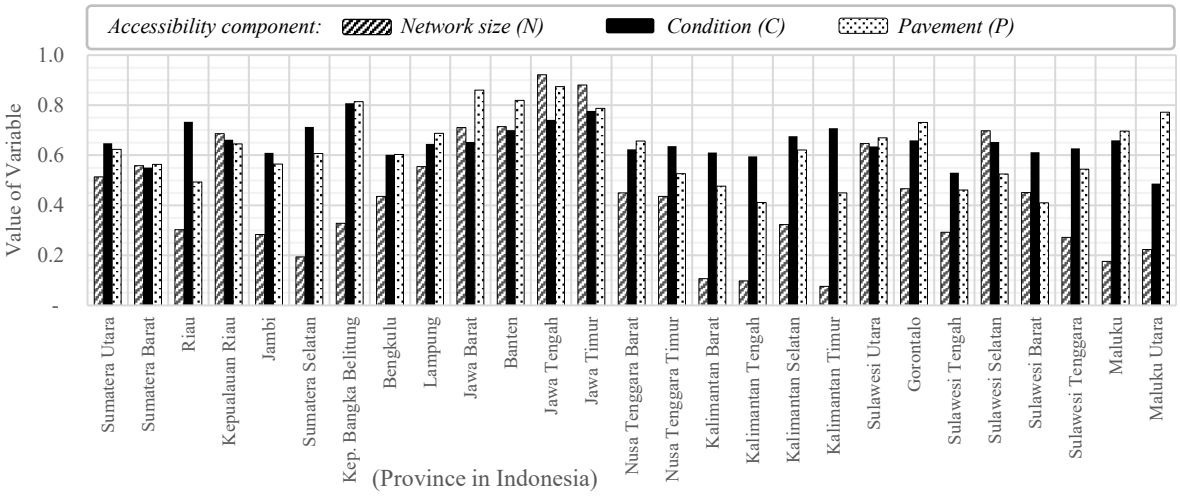
DKI Jakarta was plotted very far outside the fence “whiskers” of the box plot. It means that the extreme value may statistically be categorised as an outlier. As a consequence, this data is excluded from the dataset and further analyses.

In addition to DKI Jakarta, some provinces in Indonesia known as ‘special provinces’ obtain special treatment both in the provision of road infrastructure and financial budget for road maintenance, e.g. DI Aceh, DI Yogyakarta, Bali, Papua and Papua Barat (Kurniadi, 2012; Thiede and Gray, 2016). Although the accessibility index can still be quantified for these special provinces, the data is excluded from the calculation of national maximum or average data to provide a fair assessment between regions and to reduce errors caused by outliers in the model. Based on the distribution of accessibility components (see **Figure 6.2b**), the distribution pattern of data seems more reasonable after the capital and special provinces' were excluded. Although a variance may still exist, the disparity in the distribution of accessibility component value was not significant.



(a) All province data including special provinces

Figure 6.2 Accessibility component in Indonesia based on provinces of the year 2014



(b) All province data excluding special provinces

Figure 6.2 (Continue)

6.2.2.2 Normality test of data

The normality test is a standard statistical assessment to observe patterns of data distribution and whether they follow a normal (Gaussian) distribution or not (Santoso, 2017). The dataset is often expected to have a normal distribution because this type of distribution has the lowest uncertainty in the random value of data used as the input variable. In the normal distribution, because of the central limit theorem, the value of variables are randomly distributed around the central value resembling a bell-shaped curve. (Barbour and Röllin, 2019). The normality of data can be assessed using the Kolmogorov-Smirnov test or using a graphical method, e.g. the shape of histograms (Bowman and Robinson, 1990). In the Kolmogorov-Smirnov test, a dataset can be claimed to have normal distribution when the significance value (Sig.) is more than 0.05. In this study, as the value of 'Sig.' for each accessibility variable is more than 0.05 (see **Table 6.1**), it may be concluded that all the datasets of the accessibility components follow a normal distribution.

Table 6.1 Test of normality

Variable	Code	Kolmogorov-Smirnov [a]			
		Statistic	df	Sig.	Result
The density of road network	N_A, N_B	0.120	27	0.200 [b]	Normal
The ratio of drivable road condition	C_A	0.149	27	0.126	Normal
The ratio of paved road	P_A	0.077	27	0.200 [b]	Normal
The density of drivable road condition	C_B	0.117	27	0.200 [b]	Normal
The density of paved road	P_B	0.119	27	0.200 [b]	Normal

a. Lilliefors Significance Correction.
b. This is a lower bound of the true significance

6.2.2.3 Statistical properties of the accessibility components

The RNAI model measures the length of a road network based on three different attributes: total network length, steady-state (good or fair) road condition, and sealed pavement. Based on the statistics approach, the scale of measurement of those data are categorised as ratio data. Compared with other scales of measurement (e.g. interval, ordinal and nominal), the ratio type of measurement scale may be stated as the best category of data because it provides information about the absolute value of the object being measured. The ratio scale of measurement has a value of absolute zero so that it can be compared and used for multiplication or division. For practical assessments, this type of data offers more flexibility for any type of statistical analysis, descriptive or inferential (Dobson and Barnett, 2008).

In terms of distribution, the value of accessibility components in Indonesia are varied. As illustrated in **Table 6.2**, component N in the type B form shows a smooth linear pattern of data distributed across the value. It indicates that the variance of component N should be large. It is verifiable from the statistic descriptive result that compared to the other components, component N has the highest standard of deviation value (0.23), which may explain the high disparity level of road density between provinces in Indonesia (see **Table 6.3**).

Table 6.2 The pattern of accessibility components in Indonesia year 2014

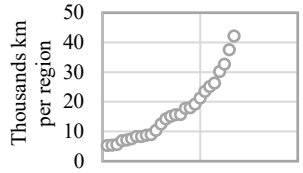
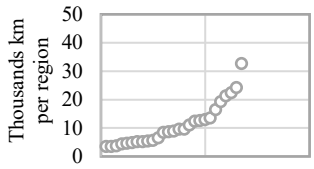
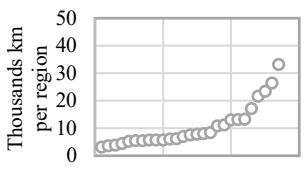
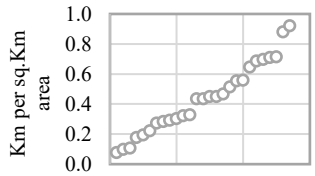
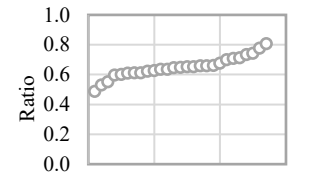
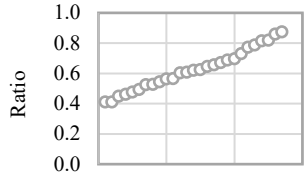
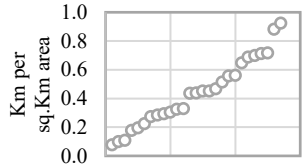
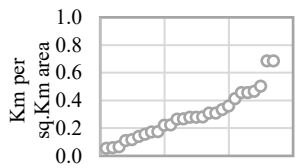
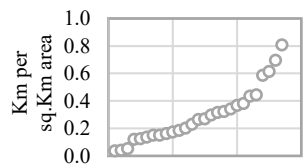
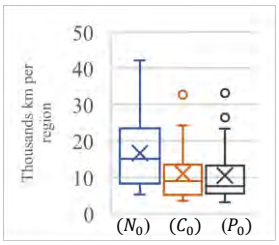
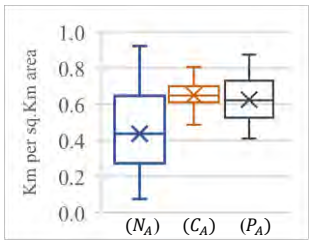
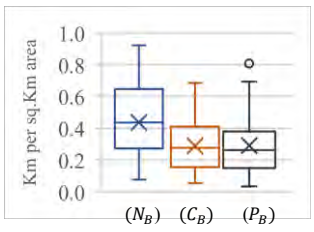
Alternative Form	Ascending Value of Accessibility Component		
	Network length (N)	Condition (C)	Pavement type (P)
[Type 0] Base form, raw data of measurement without adjustment	 N_0: Range [0-unlimited]	 C_0: Range [0- unlimited]	 P_0: Range [0- unlimited]
[Type A] The data is adjusted to fit popular indicator in road asset management	 N_A: Range [0- unlimited]	 C_A: Range [0-1]	 P_A: Range [0-1]
[Type B] The data is adjusted to fit popular indicator in infrastructure-based accessibility index	 N_B: Range [0- unlimited]	 C_B: Range [0- unlimited]	 P_B: Range [0- unlimited]

Table 6.3 Descriptive statistic of accessibility components in Indonesia year 2014

Characteristics		Alternative Form of Accessibility Component								
		Type 0			Type A			Type B		
Key difference		Raw data of measurement without adjustment (base form)			The data is adjusted to fit popular indicator in road asset management			The data is adjusted to fit popular indicator in infrastructure-based accessibility index		
Code		N_0	C_0	P_0	N_A	C_A	P_A	N_B	C_B	P_B
Unit		km	km	km	km/sq.km	km/km	km/km	km/sq.km	km/sq.km	km/sq.km
Number of data		27	27	27	27	27	27	27	27	27
Distribution		Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal
Descriptive	Min	5,250	3,461	3,104	0.08	0.49	0.41	0.08	0.05	0.03
	Max	42,107	32,737	33,163	0.92	0.81	0.87	0.92	0.68	0.81
	Mean	16,640	10,995	10,453	0.44	0.65	0.63	0.44	0.29	0.29
	Median	15,054	8,972	7,521	0.44	0.65	0.62	0.44	0.28	0.26
	Standard deviation	10,073	7,338	7,534	0.23	0.07	0.13	0.23	0.17	0.20
Box plot (box & whisker chart) [a]										

a. the" X" sign is the position of mean value in the distribution of data

Unlike the length of network component (N), the component of road condition (C) and pavement type (P) may also show a linear distribution pattern. However, the maximum value barely reaches the median of range, i.e. 0.5. It indicates the component of C and P statistically have less variance, but that the values are mostly at a low or medium-level, as seen from the position of the box to the overall data in the boxplot diagram Type B as shown in **Table 6.3**. Still, the standard deviation is high compared to the mean value.

6.2.3 Correlation Analysis

6.2.3.1 Collinearity between variables

The correlation analysis assesses the strength of the linear relationship between two variables. In multiple regression, if one predicting variable has a strong linear relationship with another predictor(s), it causes an issue known as collinearity. If the collinearity occurs, the validity of the predictor variable as an independent variable may be doubted because two or more variables are highly correlated and they may explain each other (Mazziotta and Pareto, 2013). Thus the variable may not be necessary to be included in the model because its impact is captured by the other variable(s) (Field, 2017). Moreover, as those variables are considered redundant variables, it is often suggested to drop one of them from the model (Frank and Harrell, 2015).

In general, collinearity between variables may be tested and verified through a scatter plot pattern and correlation value (e.g. Pearson correlation) between variables using a statistical tool such as SPSS software (Dohoo et al., 1997). As shown in **Table 6.4**, the scatter plot for the accessibility model Type A shows a more random pattern of relationship between components than that in Type B. In the Type B model, the scatter plot forms a linear pattern which indicates a strong linear relationship between the variables. As shown in **Table 6.5**, this collinearity issue is also confirmed by the Pearson correlation values that are close to one, i.e. 0.984 for $N_x - C_x$, 0.952 for $N_x - P_x$ and 0.968 for $C_x - P_x$. The collinearity issue in model type B remains

even after the data has been normalised using the maximum and average value, in the form of models M_1, M_2 and M_3.

Table 6.4 Correlation test for the RNAI components using a scatter plot

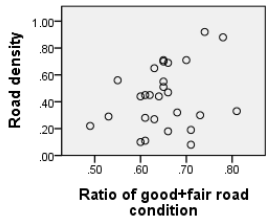
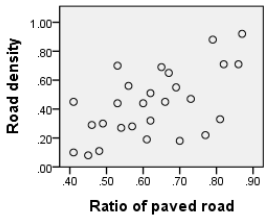
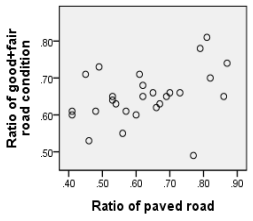
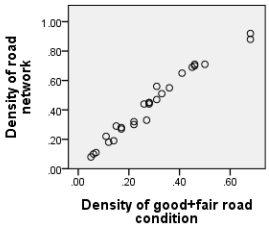
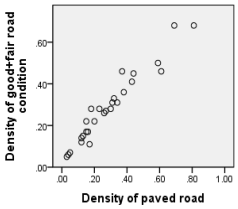
Alternative form of Accessibility components (x)	Correlation between the RNAI components or variables		
	N_x - C_x	N_x - P_x	C_x - P_x
[Type A] Popular indicator in road asset management			
[Type B] Popular indicator in accessibility measurement, i.e. road density			

Table 6.5 Pearson's correlation test for the RNAI components

Pearson correlation test*		Normalisation type (x)				
Variables	Test indicator	A	B	1	2	3
N_x *with* C_x	Correlation	0.293	0.984**	0.294	0.984**	0.984**
	Sig. (2-tailed)	0.138	0.000	0.137	0.000	0.000
	Result	No	Yes	No	Yes	Yes
N_x *with* P_x	Correlation	0.578**	0.952**	0.579**	0.954**	0.954**
	Sig. (2-tailed)	0.002	0.000	0.002	0.000	0.000
	Result	Yes	Yes	Yes	Yes	Yes
C_x *with* P_x	Correlation	0.378	0.968**	0.378	0.969**	0.968**
	Sig. (2-tailed)	0.052	0.000	0.052	0.000	0.000
	Result	No	Yes	No	Yes	Yes

** The variables are perfectly correlated when the correlation value is one (±1), and there is no correlation between variables when the correlation value is zero (0).*

*** Correlation is significant at the 0.01 level (2-tailed). The number of observations: 27.*

6.2.3.2 Dealing with collinearity issue

One of the purposes of the collinearity test is to optimise the efficiency of the model (Dobson and Barnett, 2008). The model is expected to be straightforward and free from redundant variables. Nevertheless, it must be emphasised that collinearity should be substantive, not just

technical. When collinearity inevitably exists, there are several options to deal with it, i.e. (1) checking the data to see if one of the predictor variables is a duplicate, (2) remove redundant variables (3) aggregate a similar variable, (4) increase the sample size (Dobson, 2013; Field, 2017).

In terms of the RNAI components, although the statistical analysis indicates that the components have a strong relationship. Based on the theoretical perspective, they are still independent because in practice, the length of the roads was measured using specific attributes and requirements, e.g. length of bituminous road, length of road in good condition. The strong statistical relationship might occur because these three components typically measured the length of road as the main feature and then normalised it with the same method, i.e. maximum or average value as the denominator. Considering that these three components are theoretically crucial to the concept of infrastructure-based accessibility, and the collected dataset is a population instead of a random sample data, the variables can be aggregated into a single index to address the collinearity issue. This approach is technically similar when dropping any two of the three components because they are statistically redundant. However, then it uses the average value from the three individual values (N, C, and P). Thus, the choice to use '*equal weights'* for the weighting method in the previous procedure of model development was correct (see **Chapter 5.8**). The implementation of the equal weighting method does not only satisfy the concept of equity but can deal with the collinearity issue in model Type B, i.e. models M_2 and M_3.

6.2.4 Quantification of the RNAI Model

Based on the development of the accessibility model as shown in **Chapter 5.8**, the RNAI model is calculated using three formulas, i.e. M_1, M_2 and M_3 following **Equation 5.3**, **Equation 5.4**, and **Equation 5.5**. For model M_3, to ensure the range of the index is always between zero and

one, the value of the thresholds (T_N, T_C and T_P) should be initially calculated using the maximum and mean value data for each accessibility components as shown in **Table 6.6**.

Table 6.6 The threshold and formula for the model M_3

Item	Component RNAI (x)			Total
	N_3	C_3	P_3	
Maximum road density for x	0.92	0.68	0.81	n/a
Mean of road density for x	0.44	0.29	0.29	n/a
Threshold $\left(T_x = \frac{(x)\ max}{(x)\ mean}\right)$	2.11	2.37	2.77	7.25

Formula:

$$T_N = \frac{(L_{tn}/S)\ max}{(L_{tn}/S)\ mean} = 2.11\ ;\ T_C = \frac{(L_{gf}/S)max}{(L_{gf}/S)mean} = 2.37; T_P = \frac{(L_{ac}/S)max}{(L_{ac}/S)mean} = 2.77$$

$$M_3 = \frac{\left(min\left\{T_N, \frac{(L_{tn}/S)}{(L_{tn}/S)mean}\right\} + min\left\{T_C, \frac{(L_{gf}/S)}{(L_{gf}/S)_{mean}}\right\} + min\left\{T_P, \frac{(L_{ac}/S)}{(L_{ac}/S)mean}\right\}\right)}{T_N + T_C + T_P}\ ;\ \text{range [0-1]}$$

$$M_3 = \frac{\left(min\left\{2.11, \frac{(L_{tn}/S)}{(L_{tn}/S)mean}\right\} + min\left\{2.37, \frac{(L_{gf}/S)}{(L_{gf}/S)_{mean}}\right\} + min\left\{2.77, \frac{(L_{ac}/S)}{(L_{ac}/S)mean}\right\}\right)}{7.25}\ ;\ \text{range [0-1]}$$

By implementing these threshold values in the M_3 model, the value of the accessibility index (RNAI) and its components in Indonesia for 2014 is shown in **Table 6.7,** while the accessibility index for the three models is shown in **Table 6.8**.

Table 6.7 The value of accessibility components in Indonesia based on provinces for 2014

ID	Name of province in Indonesia		Land area (sq. km)	Population density (population per sq.km)	The component of accessibility model**					
					Type A (M_1)			Type B (M_2 and M_3)		
					N_A	C_A	P_A	N_B	C_B	P_B
			(S)	(Pd)	(L_{tn}/S)	(L_{gf}/L_{tn})	(L_{ac}/L_{tn})	(L_{tn}/S)	(L_{gf}/S)	(L_{ac}/S)
1	Aceh*		57,956	84.7	0.40	0.61	0.54	0.40	0.25	0.22
2	Sumatera Utara		72,981	188.6	0.51	0.65	0.62	0.51	0.33	0.32
3	Sumatera Barat		42,013	122.2	0.56	0.55	0.56	0.56	0.31	0.31
4	Riau		87,024	71.1	0.30	0.73	0.49	0.30	0.22	0.15
5	Kepulauan Riau		8,202	233.8	0.69	0.66	0.65	0.69	0.45	0.44
6	Jambi		50,058	66.8	0.28	0.61	0.57	0.28	0.17	0.16
7	Sumatera Selatan		91,592	86.7	0.19	0.71	0.61	0.19	0.14	0.12
8	Kep. Bangka Belitung		16,424	81.8	0.33	0.81	0.81	0.33	0.27	0.27
9	Bengkulu		19,919	92.6	0.44	0.60	0.60	0.44	0.26	0.26
10	Lampung		34,624	231.8	0.55	0.65	0.69	0.55	0.36	0.38
11	DKI Jakarta*		664	15,173.4	10.55	0.64	1.00	10.55	6.73	10.55
12	Jawa Barat		35,378	1,301.1	0.71	0.65	0.86	0.71	0.46	0.61
13	Banten		9,663	1,211.3	0.71	0.70	0.82	0.71	0.50	0.59
14	Jawa Tengah		32,801	1,022.0	0.92	0.74	0.87	0.92	0.68	0.81
15	DI Yogyakarta*		3,133	1,160.8	1.37	0.77	0.79	1.37	1.05	1.08
16	Jawa Timur		47,800	807.7	0.88	0.78	0.79	0.88	0.68	0.69
17	Bali*		5,780	710.2	1.36	0.70	0.91	1.36	0.94	1.24
18	Nusa Tenggara Barat		18,572	257.0	0.45	0.62	0.66	0.45	0.28	0.30
19	Nusa Tenggara Timur		48,718	103.4	0.44	0.64	0.53	0.44	0.28	0.23
20	Kalimantan Barat		147,307	32.0	0.11	0.61	0.48	0.11	0.07	0.05
21	Kalimantan Tengah		153,565	15.9	0.10	0.60	0.41	0.10	0.06	0.04
22	Kalimantan Selatan		38,744	101.2	0.32	0.68	0.62	0.32	0.22	0.20
23	Kalimantan Timur		204,534	19.4	0.08	0.71	0.45	0.08	0.05	0.03
25	Sulawesi Utara		13,852	172.3	0.65	0.63	0.67	0.65	0.41	0.43
26	Gorontalo		11,257	99.1	0.47	0.66	0.73	0.47	0.31	0.34
27	Sulawesi Tengah		61,841	45.8	0.29	0.53	0.46	0.29	0.15	0.13
28	Sulawesi Selatan		46,717	180.5	0.70	0.65	0.53	0.70	0.46	0.37
29	Sulawesi Barat		16,787	74.9	0.45	0.61	0.41	0.45	0.28	0.18
30	Sulawesi Tenggara		38,068	64.3	0.27	0.63	0.54	0.27	0.17	0.15
31	Maluku		46,914	35.3	0.18	0.66	0.70	0.18	0.12	0.12
32	Maluku Utara		31,983	35.6	0.22	0.49	0.77	0.22	0.11	0.17
33	Papua*		319,036	9.7	0.05	0.47	0.39	0.05	0.03	0.02
34	Papua Barat*		97,024	8.8	0.09	0.61	0.47	0.09	0.05	0.04
ALL Province (with outlier)		min	664	9	0.05	0.47	0.39	0.05	0.03	0.02
		max	319,036	15,173	10.55	0.81	1.00	10.55	6.73	10.55
		average	57,907	724	0.78	0.65	0.64	0.78	0.51	0.64
Exclude special province (without outliers)		min	8,202	16	0.08	0.49	0.41	0.08	0.05	0.03
		max	204,534	1,301	0.92	0.81	0.87	0.92	0.68	0.81
		average	52,864	250	0.44	0.65	0.63	0.44	0.29	0.29

** The status for this province in Indonesia is a special province. Thus, this data was excluded in calculating the national data (mean, max).*

*** Accessibility component: N = network size; C = condition; P = pavement type.*

Table 6.8 Accessibility in Indonesia based on provinces in the year 2014

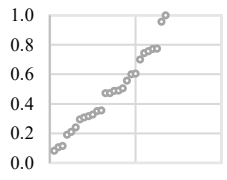
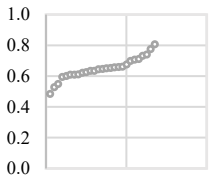
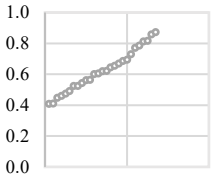
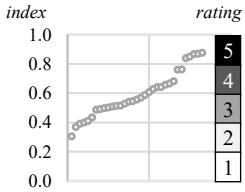
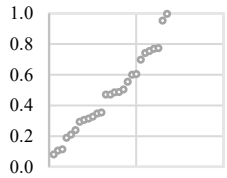
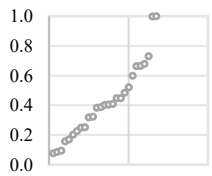
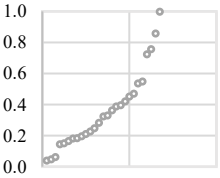
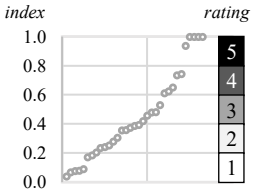
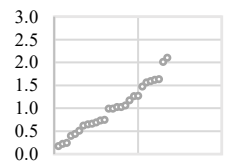
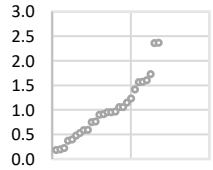
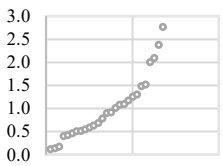
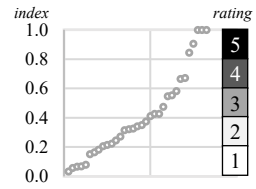
ID	Name of province	Accessibility Component**									Accessibility Value (RNAI)					
		M_1			M_2			M_3			Index			Rating		
		N_1	C_1	P_1	N_2	C_2	P_2	N_3	C_3	P_3	M_1	M_2	M_3	M_1	M_2	M_3
1	Aceh*	0.44	0.61	0.54	0.44	0.36	0.27	0.93	0.86	0.75	0.53	0.36	0.32	3	2	2
2	Sumatera Utara	0.56	0.65	0.62	0.56	0.49	0.40	1.17	1.15	1.10	0.61	0.48	0.43	4	3	3
3	Sumatera Barat	0.61	0.55	0.56	0.61	0.45	0.39	1.28	1.06	1.08	0.57	0.48	0.43	3	3	3
4	Riau	0.33	0.73	0.49	0.33	0.32	0.19	0.69	0.77	0.51	0.52	0.28	0.25	3	2	2
5	Kepulauan Riau	0.74	0.66	0.65	0.74	0.66	0.55	1.57	1.57	1.52	0.68	0.65	0.58	4	4	3
6	Jambi	0.31	0.61	0.57	0.31	0.25	0.20	0.65	0.60	0.55	0.49	0.25	0.22	3	2	2
7	Sumatera Selatan	0.21	0.71	0.61	0.21	0.20	0.15	0.44	0.48	0.40	0.51	0.19	0.17	3	1	1
8	Kep. Bangka Belitung	0.36	0.81	0.81	0.36	0.39	0.33	0.75	0.92	0.92	0.66	0.36	0.32	4	2	2
9	Bengkulu	0.47	0.60	0.60	0.47	0.38	0.33	1.00	0.91	0.90	0.56	0.39	0.35	3	2	2
10	Lampung	0.60	0.65	0.69	0.60	0.52	0.47	1.27	1.24	1.31	0.64	0.53	0.48	4	3	3
11	DKI Jakarta*	1.00	0.64	1.00	1.00	1.00	1.00	2.50	2.50	3.00	0.88	1.00	1.00	5	5	5
12	Jawa Barat	0.77	0.65	0.86	0.77	0.68	0.76	1.63	1.61	2.10	0.76	0.74	0.67	4	4	4
13	Banten	0.78	0.70	0.82	0.78	0.73	0.73	1.64	1.73	2.01	0.76	0.74	0.67	4	4	4
14	Jawa Tengah	1.00	0.74	0.87	1.00	1.00	1.00	2.11	2.37	2.77	0.87	1.00	0.91	5	5	5
15	DI Yogyakarta*	1.00	0.77	0.79	1.00	1.00	1.00	2.50	2.50	3.00	0.85	1.00	1.00	5	5	5
16	Jawa Timur	0.96	0.78	0.79	0.96	1.00	0.86	2.02	2.37	2.38	0.84	0.94	0.85	5	5	5
17	Bali*	1.00	0.70	0.91	1.00	1.00	1.00	2.50	2.50	3.00	0.87	1.00	1.00	5	5	5
18	Nusa Tenggara Barat	0.49	0.62	0.66	0.49	0.41	0.37	1.03	0.97	1.01	0.59	0.42	0.38	3	3	2
19	Nusa Tenggara Timur	0.47	0.64	0.53	0.47	0.40	0.28	1.00	0.96	0.79	0.54	0.39	0.34	3	2	2
20	Kalimantan Barat	0.12	0.61	0.48	0.12	0.10	0.06	0.24	0.23	0.18	0.40	0.09	0.08	3	1	1
21	Kalimantan Tengah	0.11	0.60	0.41	0.11	0.09	0.05	0.22	0.20	0.14	0.37	0.08	0.07	2	1	1
22	Kalimantan Selatan	0.35	0.68	0.62	0.35	0.32	0.25	0.74	0.76	0.69	0.55	0.31	0.27	3	2	2
23	Kalimantan Timur	0.08	0.71	0.45	0.08	0.08	0.04	0.17	0.19	0.12	0.41	0.07	0.06	3	1	1
25	Sulawesi Utara	0.70	0.63	0.67	0.70	0.60	0.54	1.48	1.42	1.49	0.67	0.61	0.55	4	4	3
26	Gorontalo	0.51	0.66	0.73	0.51	0.45	0.42	1.07	1.06	1.17	0.63	0.46	0.41	4	3	3
27	Sulawesi Tengah	0.32	0.53	0.46	0.32	0.23	0.17	0.67	0.54	0.46	0.44	0.24	0.21	3	2	2
28	Sulawesi Selatan	0.76	0.65	0.53	0.76	0.67	0.45	1.60	1.58	1.26	0.65	0.63	0.55	4	4	3
29	Sulawesi Barat	0.49	0.61	0.41	0.49	0.40	0.23	1.03	0.96	0.63	0.50	0.37	0.33	3	2	2
30	Sulawesi Tenggara	0.30	0.63	0.54	0.30	0.25	0.18	0.62	0.59	0.51	0.49	0.24	0.22	3	2	2
31	Maluku	0.19	0.66	0.70	0.19	0.17	0.15	0.40	0.40	0.42	0.52	0.17	0.15	3	1	1
32	Maluku Utara	0.24	0.49	0.77	0.24	0.16	0.21	0.51	0.37	0.59	0.50	0.20	0.18	3	2	1
33	Papua*	0.06	0.47	0.39	0.06	0.04	0.03	0.12	0.09	0.07	0.31	0.04	0.04	2	1	1
34	Papua Barat*	0.10	0.61	0.47	0.10	0.08	0.05	0.21	0.19	0.14	0.39	0.08	0.07	2	1	1
Average	Exclude SP	0.47	0.65	0.63	0.47	0.42	0.36	1.00	1.00	1.00	0.58	0.42	0.38	3	3	2
	Include SP	0.50	0.65	0.64	0.50	0.45	0.40	1.08	1.08	1.12	0.59	0.45	0.41	3	3	3

** The status for this province in Indonesia is a special province. Thus, this data was excluded in calculating the national average value.*
*** Accessibility component: N = network size; C = condition; P = pavement type. SP= special province*

Based on **Table 6.8**, the accessibility level by province in Indonesia in 2014 was typically at a moderate level (rating 3 out of 5). By looking at the distribution from the three alternative model outputs (see **Table 6.9**), the accessibility value in the M_2 and M_3 models shows a more distributed pattern across the range [1 to 5] than the M_1 model. It means that the M_2 and M_3 are

more sensitive and provide a better comparison of accessibility between provinces because they represent the entire range of accessibility values.

Table 6.9 The value of the accessibility index and its components in Indonesia

Model	Component of Accessibility			Accessibility Index (RNAI)
	Network (N)	Condition (C)	Pavement (P)	
M_1				
M_2				
M_3				

In terms of model outputs, each model produces different output values even though they use the same data as input. Theoretically, because each model has a specific formula, e.g. due to the different techniques of normalisation, the value of the index is expected to be different. However, the star rating category should be similar. Consequently, the three models need to be tested further using a random combination of inputs to check their robustness and evaluate whether the output is still valid and that it satisfies the theoretical concept of accessibility, e.g. when extreme values are encountered.

6.3 Step 7: Robustness Test for the RNAI Model

6.3.1 Uncertainty in the Combination of Input Variables

The RNAI model is constructed from several indicators, and the values of the input variables of the model are varied and random. Consequently, a combination of uncertainty in the input

variables may cause severe errors in the structure, quantification and the output of a model. Hence, to assess the robustness of the RNAI model, it is necessary to ensure the model can function appropriately in the presence of invalid inputs (Chatfield, 2018). In this case, a combination of extreme values represents the unusual combination of inputs as the worst-case scenario. Since the value of the RNAI components range from zero to one [0-1], the extreme values are set using a combination of very low (VL=0.1), very high (VH=0.9), and extremely high (Outlier=1.8). The detail of the robustness test is shown in **Table 6.10**.

Table 6.10 Robustness test of accessibility model using extreme values

Accessibility component				Accessibility value (RNAI)**						Expected value (RNAI rating)	Result
Road density (km/sq.km)		Ratio good & fair (km/km)	Ratio sealed road (km/km)	Index [0 to 1]			Rating [1 to 5]				
[N]		[C]	[P]	M1	M2	M3	M1	M2	M3		
Very low	0.1	0.1	0.1	0.10	0.05	0.04	1	1	1	1	ok
	0.1	0.1	0.9	0.37	0.08	0.07	2	1	1	1, 2	ok
	0.1	0.9	0.1	0.37	0.08	0.07	2	1	1	1, 2	ok
	0.1	0.9	0.9	0.64	0.12	0.11	4^{r}	1	1	1, 2, 3	rejected
Very high	0.9	0.1	0.1	0.39	0.41	0.33	2	3	2	2, 3	ok
	0.9	0.1	0.9	0.66	0.70	0.64	4	4	4	3, 4	ok
	0.9	0.9	0.1	0.66	0.70	0.61	4	4	4	3, 4	ok
	0.9	0.9	0.9	0.93	0.99	0.92	5	5	5	5	ok
Extreme high (outlier)	1.8	0.1	0.1	0.40	0.50	0.47	2	3	3	2, 3	ok
	1.8	0.1	0.9	0.67	0.75	0.77	4	4	4	3, 4	ok
	1.8	0.9	0.1	0.67	0.74	0.70	4	4	4	3, 4	ok
	1.8	0.9	0.9	0.93	1.00	1.00	5	5	5	5	ok
Median	0.50	0.50	0.50	0.51	0.41	0.36	3	3	2^{r}	3	rejected

**VH = Very High (assume=0.9); VL = Very Low (assume=0.1); extreme high, outlier (assume=1.8)*
***M1 = Model 1, M2 = Model 2; M3= Model 3; Accessibility rating:1= very low; 2= low; 3= medium; 4= high; 5= very high; r = theoretically rejected. The land area assumed 50,000 sq.km*

Based on **Table 6.10**, the only model that meets all the requirements is model M_2. The model M_2 always generated a correct accessibility result in the presence of any combination of inputs. Model M_1 and M_3 were theoretically rejected because they violated the expected value of the accessibility index. For instance, although all roads are sealed and in excellent condition (C and P are high), if the road density is limited (N is very low), e.g. only 0.1 km per sq.km, the accessibility of region may remain low. In practice, the road may only connect two provincial

capitals, but not sufficiently connect other services like markets within the province. Thus, the output from M_1 represents this condition and a high level of accessibility was rejected due to violating the theoretical concept of accessibility. Meanwhile for M_3, since the RNAI is a linear model which has a star rating value ranging from one to five [1-5], the output was expected to be a three-star rating (representing the mid-range point) when a median value was used as the input. Accordingly, the model M_3 which gave a two-star rating as the output did not satisfy the concepts of linear index and accessibility.

6.3.2 Robustness of the RNAI Formula

6.3.2.1 Normalisation method

In the normalisation procedure, all three alternative models use the 'distance to a reference point' method as the benchmark. The different is, the M_1 and M_2 models use the 'maximum' value while M_3 uses the 'mean' value. For a historical comparison (annual or periodical such as five years), the choice to use the 'maximum' value as a reference point (benchmark) is more robust because it is steadier and more stable than the 'mean' value, which is statistically more sensitive to changes in variables. The maximum value may only be altered if there is a change in one specific data (i.e. the maximum value); otherwise, it always remains constant.

The reference point that was used as a denominator varies each year, the quantification of the accessibility index using the M_3 model is more complicated than using the M_1 and M_2 models. In terms of equity, it is also not fair to compare year to year (historical value) because the average value as the reference point tends to be different each year. Therefore, M_1 and M_2 are more robust for the normalisation method than the M_3 model. As an alternative solution, the reference point (maximum value) may be set constant as the base of comparison for accessibility development in the last decade, e.g. relative to the maximum value of accessibility

components in 2010 to compare accessibility levels in a region on year by year basis such as the improvement of accessibility level in province 'X' in the last five years (2014-2019).

6.3.2.2 The threshold value in the M_3 model

Unlike the model M_1 and M_2 which has a fixed threshold value, i.e. maximum one, the formula for the M_3 model is more influenced by the distribution of data, i.e. the value of maximum and minimum for each component to determine the threshold value (T_x). This inconsistent formula may be a weakness of the M_3 model because it influences the weighting factor for each component and violates the concept of equity. Due to different types of data distribution, the formula may unexpectedly put more weight on the component, which has a higher value of standard deviation. Consequently, the M_1 and M_2 models are preferred because they offer better stability in the range of components and weighting factors than the M_3 model.

6.3.2.3 Adjustment of formula in the RNAI model

Based on the overall result of the robustness test in the previous subchapters, the M_2 model is more robust and superior than M_1 and M_3. However, it may be argued that the use of threshold in the RNAI formula, i.e. maximum is 1.0, for each component may not be required. Accordingly, this section simulates how the model behaves when the threshold (maximum=1.0) is removed from the formula. The adjustment of the RNAI formula using the scenario with and without a threshold is shown in **Table 6.11,** and the distribution of the calculation results using Indonesia as the case study can be seen in **Figure 6.3**.

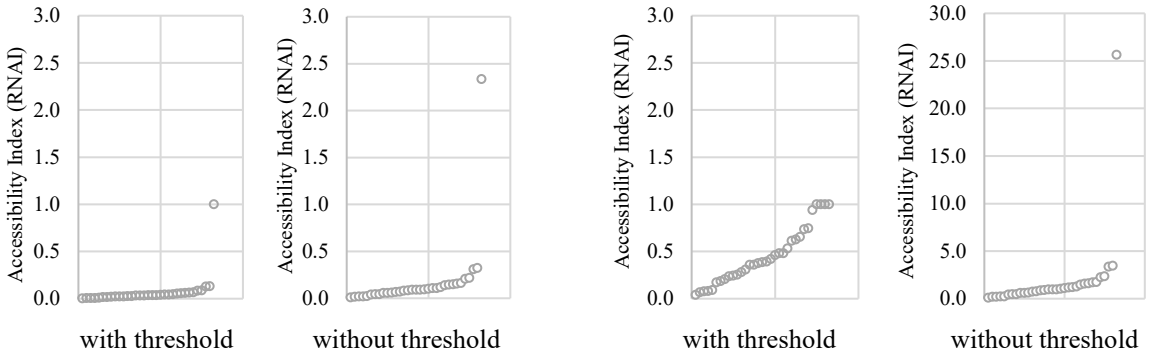
Based on the calculation results, the distribution of the RNAI value from the "with threshold" formula offers a smooth linear pattern of data which distributed equally across the range and the value consistently ranges from zero to one [0-1]. The result for the calculation without a threshold shows the index value is not distributed across the range, and there is a big gap without

value. The presence of the threshold (maximum=1.0) for each of the components successfully limits the range between zero and one, which makes the model more robust and stable.

Table 6.11 Adjustment of formula in the RNAI model

Adjustment	Formula*
Original Formula (with threshold)	$M_2 = \frac{1}{n} \times \sum_{x=1}^{n} min\left\{1, \frac{RD_x}{max\ \mathrm{RD}_x}\right\}$ $M_2 = \frac{1}{3} \times \left(min\left\{1, \frac{(L_{tn}/S)}{(L_{tn}/S)_{max}}\right\} + min\left\{1, \frac{(L_{gf}/S)}{(L_{gf}/S)_{max}}\right\} + min\left\{1, \frac{(L_{ac}/S)}{(L_{ac}/S)_{max}}\right\} \right)$
Simplified Formula (without threshold)	$M_{2\ \text{without threshold}} = \frac{1}{n} \times \sum_{x=1}^{n} \frac{RD_x}{max\ RD_x}$ $M_{2\ \text{without threshold}} = \frac{1}{3} \times \left(\frac{(L_{tn}/S)}{(L_{tn}/S)_{max}} + \frac{(L_{gf}/S)}{(L_{gf}/S)_{max}} + \frac{(L_{ac}/S)}{(L_{ac}/S)_{max}} \right)$

** Where x=1,2,3; $RD_1 = N$; $RD_2 = C$; $RD_3 = P$; RD=road density.*



a) Outlier data are used (included) in calculating the maximum threshold

b) Outlier data are excluded in calculating the maximum threshold

Figure 6.3 Distribution of accessibility index in Indonesia using the scenario of with and without threshold value

Overall, the results show that the threshold value (maximum=1.0) may be removed from the formula when there is no outlier in the database. However, for general application, it is recommended to keep the threshold (maximum=1.0) within the formula to anticipate the presence of unexpected outliers. The overall results of the robustness test are resumed in **Table 6.12**.

Table 6.12 The resume of the robustness test outcomes

Robustness test	Alternative model		
	M_1	M_2	M_3
Uncertainty in inputs variable (extreme value)	failed	OK	failed
Normalisation method	OK	OK	failed
Threshold value	OK	OK	failed

6.4 Accessibility Relative to International Benchmark

An accessibility index relative to an international benchmark is an accessibility measurement which calculates the accessibility level between countries by using a specific country as a benchmark. In this study, the calibration factors were developed based on road network density data from the World Bank and OECD. The road network data includes all roads category within the country, e.g. motorways, highways, national (primary) roads, regional (secondary) roads, and other urban and rural roads.

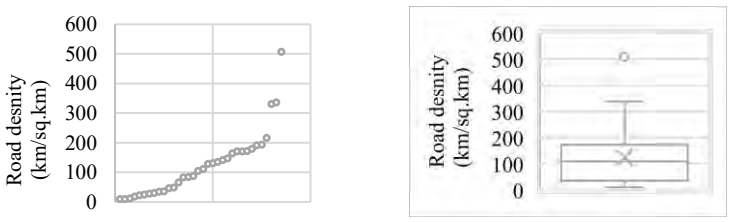
Concerning the reliability of data, the reported road asset database published by the World Bank and OECD is arguably inaccurate. The reported data may vary in accuracy and consistency because each country has specific characteristics and standards of road assets like the functional classification of roads in the United Kingdom as a developed European country compared with Indonesia as a developing Asian country. In these cases, data is often not suitable for comparison. Accordingly, in applications, the functional classification of a country's road network must be carefully examined before transfer applications and it is necessary to scrutinize each case. Based on the road density value, the calibration factor for comparing accessibility level relatively between countries is shown in **Table 6.13**.

Based on the global distribution data of road density, road density by country typically ranges from 10 to 200 with an average value of around 100 km of road per 100 square km. Although some values above 200 exist, based on the distribution of data, these values are categorised as outliers (see box plot diagram in **Figure 6.4**).

Table 6.13 Calibration factor for different countries and benchmarks

Country (X)	Road density (km/100 km2) b			Calibration factor for country-x (θ_{ZX}) based on country-Z as a benchmark			
	OECD (Y-2014)	The World Bank (Y-2011)	Maximum	Japan (337.1)	UK (172.3)	US (66.7)	OECD Asia (28)
Belgium	508	504.5	508.4	1.51	2.95	7.62	18.16
Japan [a]	337	n/a	337.1	1.00	1.96	5.05	12.04
Netherlands	331	331.5	331.5	0.98	1.92	4.97	11.84
Hungary	217	216.0	217.1	0.64	1.26	3.25	7.75
France	194	191.6	194.1	0.58	1.13	2.91	6.93
Slovenia	192	192.6	192.6	0.57	1.12	2.89	6.88
Germany	180	180.2	180.3	0.53	1.05	2.70	6.44
Switzerland	173	173.1	173.3	0.51	1.01	2.60	6.19
The United Kingdom [a]	172	172.3	172.3	0.51	1.00	2.58	6.15
Denmark	172	171.6	171.9	0.51	0.99	2.58	6.14
Czech Republic	166	165.7	165.7	0.49	0.96	2.48	5.92
Austria	148	136.6	148.0	0.44	0.86	2.22	5.28
India	n/a	142.7	142.7	0.42	0.83	2.14	5.10
Ireland	137	n/a	136.6	0.41	0.79	2.05	4.88
Poland	132	131.8	132.2	0.39	0.77	1.98	4.72
Estonia	130	129.3	129.9	0.39	0.75	1.95	4.64
Luxembourg	112	n/a	111.9	0.33	0.65	1.68	4.00
Korea	106	106.0	106.1	0.31	0.62	1.59	3.79
Greece	89	88.6	88.6	0.26	0.51	1.33	3.17
Israel	85	84.1	85.3	0.25	0.49	1.28	3.05
Italy	85	n/a	84.8	0.25	0.49	1.27	3.03
The United States [a]	67	66.7	66.7	0.20	0.39	1.00	2.38
Turkey	50	47.3	49.6	0.15	0.29	0.74	1.77
Malaysia	n/a	47.0	47.0	0.14	0.27	0.70	1.68
Slovak Republic	37	n/a	36.6	0.11	0.21	0.55	1.31
New Zealand	35	35.2	35.3	0.10	0.20	0.53	1.26
Finland	32	n/a	31.6	0.09	0.18	0.47	1.13
Norway	24	29	29.0	0.09	0.17	0.43	1.04
Indonesia	n/a	26.1	26.1	0.08	0.15	0.39	0.93
Portugal	15	24.1	24.1	0.07	0.14	0.36	0.86
Mexico	19	n/a	19.3	0.06	0.11	0.29	0.69
Iceland	13	12.5	12.5	0.04	0.07	0.19	0.45
Australia	11	10.6	11.3	0.03	0.06	0.17	0.40
Chile	10	10.3	10.3	0.03	0.06	0.15	0.37
OECD	43	n/a	43	0.13	0.25	0.65	1.55
OECD America	36	n/a	36	0.11	0.21	0.54	1.28
OECD Asia-Oceania [a]	28	n/a	28	0.08	0.16	0.42	1.00
OECD Europe	102	n/a	102	0.30	0.59	1.53	3.64

a Potential to be used as a benchmark country (z); OECD Asia Oceania ≈ Indonesia → Indonesia may represent Asian country
b Based on OECD (2015c) and World Bank (2015)



(a) Scater plot (b) Box plot (box & whisker)

Figure 6.4 Distribution of worldwide road density

In general, any country may be nominated as a benchmark. However, it is more practical if it has a road density value which represents an exceptional value from the worldwide distribution such as the maximum or average value. Alternatively, typical countries, that are often referred to as international benchmarks like the USA or the UK may also be considered. In this study, because the case study was Indonesia and because most developing countries are located in Asia and Africa (see **Figure 3.3**), the OECD Asian-Oceanian data was deemed the most appropriate to be the benchmark. The value of the accessibility index in Indonesia by province relative to OECD Asian-Oceania is shown in **Figure 6.5**.

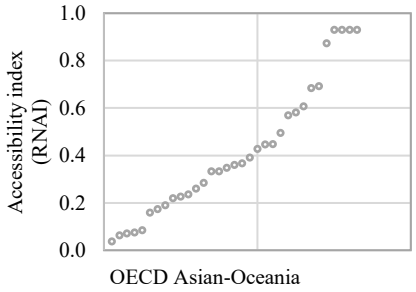


Figure 6.5 Accessibility index in Indonesia relative to international benchmark

Figure 6.5 shows that the calibrated values are equally spread across the range, which indicates that the calibrated values sensitivity is sufficient to describe and represent varying levels of accessibility in Indonesia. Thus, the use of OECD Asian-Oceania as the international benchmark was considered the best approach to compare accessibility levels between countries.

6.5 Summary

The procedure of model testing for the RNAI model is presented in this chapter using a dataset from Indonesia. Although models M_1, M_2 and M_3 have similar components, the composite indicators procedure to develop the M_2 model functions by quantifying the accessibility level in the form of road density and using maximum national data as the benchmark, which has a

significant impact on the robustness of the model. Compared to models M_1 and M_3, the robustness test showed that M_2 was the best fit to represent the actual condition of the accessibility level in Indonesia. M_2 was still valid for any random combination value of accessibility components, even in the presence of outliers. The option to select road density as the base form of accessibility component in M_2 demonstrates that it can increase the practical implementation and satisfy the concept of equity by using a provincial region as the unit of analysis. Also, M_2 could be claimed to be an enhanced model compared to current popular accessibility models like the one developed by the World Bank based on road density. As the characteristics and standard of road assets in each country vary, M_2 improves the existing World Bank model by introducing additional components to measure the accessibility level, i.e. density of road with a good and fair condition (C) and the density of road with a sealed (paved) road surface (P) in addition to the density of the road network (total road length). Further comparisons between those two models are elaborated in **Chapter 9.3**.

In terms of international comparison, the value of the accessibility index in Indonesia may also be converted relative to OECD Asian-Oceania countries using a calibration factor of (θ_{ZX} = 0.93). However, since each country has specific characteristics and standards of road assets, the functional classification of a country's road network must be carefully examined before transfer applications, and it is necessary to scrutinize each case.

CHAPTER 7

SENSITIVITY AND SCENARIO ANALYSIS

7.1 Introduction

This chapter presents the sensitivity and scenario analyses for the RNAI model, which are performed to find out the best strategy for optimising the overall outcomes of the model. The sensitivity analysis identifies the most sensitive parameter in the RNAI Model, and the scenario analysis assesses how the roadwork standards and road degradation scenarios affect the overall level of accessibility. In general, the more sensitive the parameter, the more significant the impact of the parameter to the model (Saltelli et al., 2004). By understanding that relationship, maintenance standards and strategies for managing road assets may be adjusted by giving a higher priority or weight to the most sensitive parameter in the RNAI model as the primary strategy for accessibility improvement. However, as the action plan should also follow some technical standards in road asset management, the available options of roadworks may affect some accessibility components immediately. Thus, in managing road network accessibility, it is better to consider and accommodate these circumstances through a scenario analysis.

This chapter consists of four sections. Foremost, it presents the sensitivity analysis using three different techniques (regression, one-at-a-time, and the Monte Carlo simulation) to identify the most sensitive parameter of the RNAI model. Subsequently, a scenario analysis is presented to demonstrate how existing roadwork standards may be associated with the changes in inputs and how they affect the overall output of the accessibility model.

7.2 Sensitivity Analysis

Sensitivity analysis captures the effect of changes in input variables on the overall output of a model (Frey and Patil, 2002). This analysis is required to provide a better understanding of relationships between input and output variables in the RNAI model so that if an unexpected relationship is encountered, the problem can be resolved accordingly. There are several approaches to perform a sensitivity analysis, but they are broadly classified into "local" and "global" sensitivity analyses (McKenzie et al., 2019). A "local" sensitivity analysis, which known as one-at-a-time (OAT) technique, addresses sensitivity relative to one point of parameter values. In contrast, a "global" sensitivity analysis examines sensitivity relative to the entire parameter distribution, e.g., using the Monte Carlo simulation (Hamby, 1995). Since they support each other, those two sensitivity analysis approaches are used to assess the RNAI Model in this research. Also, as the RNAI uses a linear mathematical model to measure accessibility, a regression analysis can assess the sensitivity of the RNAI model (Xu and Gertner, 2008; Iooss and Lemaître, 2015).

7.2.1 Regression Analysis

Regression analysis is often the simplest and most common technique for identifying the most sensitive parameters in a linear model (Saltelli, 2002). This technique, however, may only be accurate in the condition that the regression matches the response of the model indicated by the value of coefficient determination (R^2) close to one. In applications, if the model has several indicators, a stepwise method can exclude unimportant variables from the model using a statistical tool, e.g., SPSS software (Frey and Patil, 2002). In this case, observing the order in which variables are added or removed provides valuable information about the quality of the predictor variables.

How well the regression model fits the data can be assessed by the value of R^2 (Bowman and Robinson, 1990). The closer the value is to one, the better the regression model is. However, in the multiple regression analysis, the coefficient of determination (R^2) always increases when a predictor variable is added to the model, even if the variable does not improve the overall model (Weisberg, 2005). Consequently, a model that has a higher number of variables always looks like a better model due to having a higher R^2 value. To address this issue, the *adjusted* R^2 value can be used to check as it only increases when a new predictor variable enhances the model (Frank and Harrell, 2015).

Based on the stepwise regression analysis results (see model summary table in **Figure 7.1**), the statistical tool generated three regression models that may be used to predict the RNAI values. By looking at the coefficient of determination values (R^2), the three models have R^2 values close to one which indicates that the total variation in the dependent variable is well explained by the independent variables from the three models. As previously anticipated, the R^2 value increased when the predictor variable was added to the model but the increase of the *adjusted* R^2 level was not significant, i.e. adding the second predictor raises it by 0.007 points (0.989 to 0.996) and adding the third predictor raises it further by 0.004 points (0.996 to 1.000). It means that predicting the RNAI values using the C variable as the main predictor (Model-1) may be sufficient (R^2=0.989) but predicting the RNAI values using N, C, and P variable as the predictors may be better as Model-3 offers the best R^2 and *adjusted* R^2 values (R^2 =*adjusted* R^2=1.000) with the lowest chance of error estimation (0.373%).

In the context of sensitivity analysis, the degree of sensitivity for each parameter is directly assessed and compared on an equal basis from the regression coefficient values (B) (Frey and Patil, 2002). The higher the regression coefficient of a variable (B), the more significant the contribution of the variable to the model is. According to the regression analysis results (see

the coefficients table in **Figure 7.1**), the most sensitive variable is C variable (B=0.503), followed by P (B=0.416) and N (B=0.350). In term of impact contribution, as confirmed by the Standardized Coefficients Beta value, the change in the C variable may give the greatest contribution to the overall change in the RNAI values, i.e. 34.5% (Standardized coef. Beta=0.345), followed by P (33.6%) and N (33.0%).

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.994[a]	.989	.989	.02659
2	.998[b]	.996	.996	.01575
3	1.000[c]	1.000	1.000	.00373

a. Predictors: (Constant), C; b. Predictors: (Constant), C, P; c. Predictors: (Constant), C, P, N.

Coefficients [a]

Model		Unstandardised Coefficients B	Unstandardised Coefficients Std. Error	Standardised Coefficients Beta	t	Sig.
1	(Constant)	.000	.010		-.036	.972
	C	1.451	.031	.994	47.457	.000
2	(Constant)	.016	.006		2.439	.022
	C	.974	.072	.667	13.568	.000
	P	.418	.061	.338	6.870	.000
3	(Constant)	.000	.002		-.180	.858
	C	.503	.029	.345	17.421	.000
	P	.416	.014	.336	28.865	.000
	N	.350	.017	.330	20.151	.000

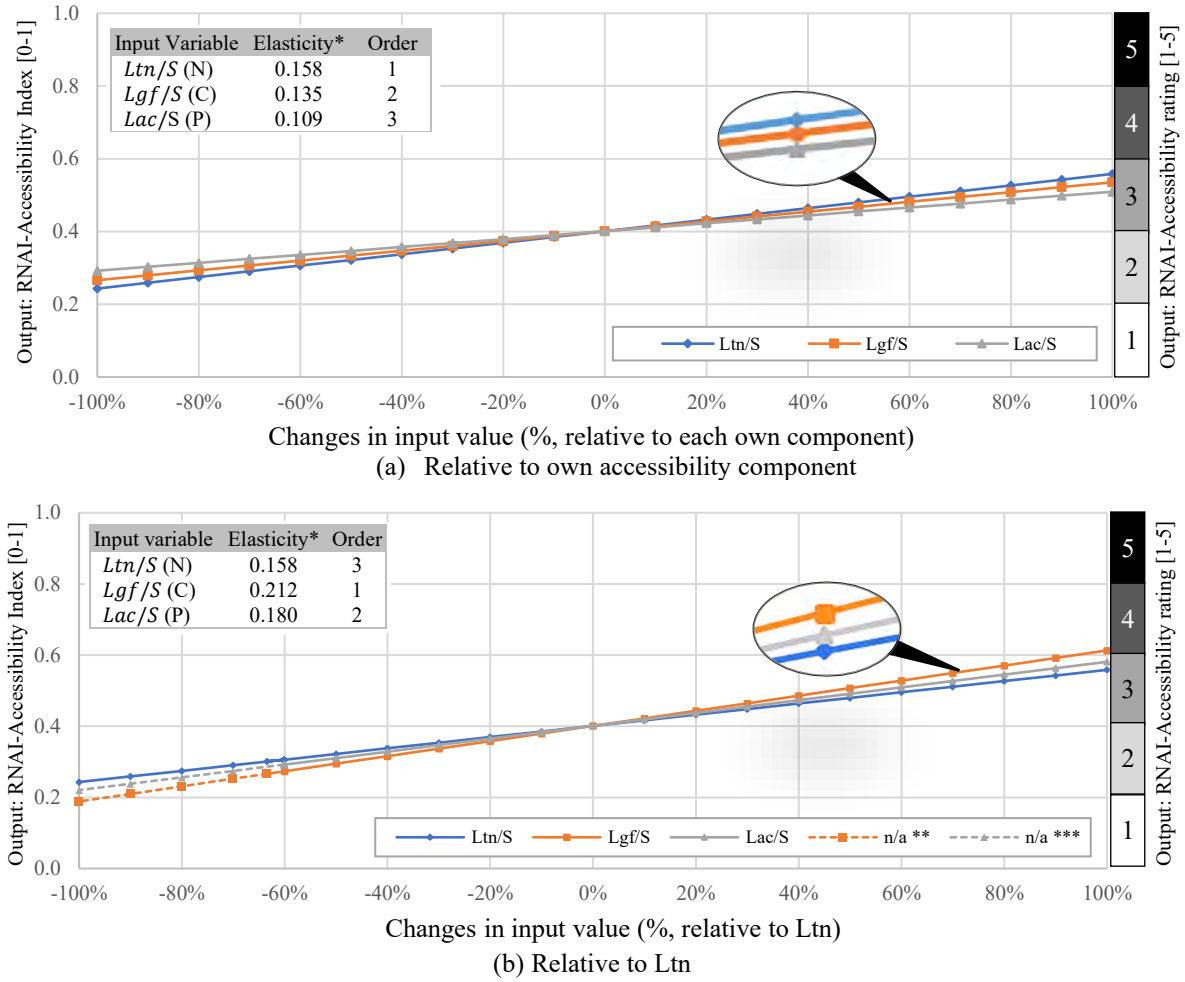
a. Dependent Variable: RNAI
$N = Ltn/S$ (network); $C = Lgf/S$ (condition); $P = Lac/S$ (pavement).

Figure 7.1 The output of multiple regression analysis using the SPSS software

7.2.2 One-at-a-time (OAT) Sensitivity Measures

One-at-a-time (OAT) is the most straight forward approach for sensitivity measures (Link et al., 2018). This technique is often preferred due to practical reasons because it minimises the chances of computer program crashes, especially when several input factors are changed simultaneously (Saltelli et al., 2010). In general, OAT tries to find out the impact of changes in one parameter at a time while other parameters remain constant (Hamby, 1994). The value of changing parameter is typically changed relative to a base case value, e.g., +/- 20%, 40%, 60%, 80%, and 100%. The base case scenario is based on the "median" or predefined "existing

values" (Oracle, 2017). As the objective is to assess a general condition, the median value may be preferred as the base case scenario (Ln/s=0.436, Lgf/S=0.276, and Lac/S=0.263) to reflect the typical accessibility condition in Indonesia. The overall results of the OAT sensitivity analysis are shown in **Figure 7.2**.



** Elasticity is the gradient of the sensitivity line ($m = y/x$). The higher the value of elasticity, the more sensitive the variable is.*
*** not available due to maximum available length of good or fair condition of roads as the base of analysis (i.e. 13,817 km or 63.37%).*
**** not available due to maximum available length of sealed or paved roads as the base of analysis (i.e. 13,138 km or 60.26%). Land area is assumed 50,000 sq.km following the mean value of the provincial area in Indonesia.*

Figure 7.2 One-at-a-time (OAT) sensitivity measures for the RNAI model

In the graphical presentation of the sensitivity analysis, the more sensitive the parameters, the higher the gradient of the sensitivity line (elasticity value) is. Based on the OAT analysis (see **Figure 7.2**), the result shows a different outcome for two different approaches of changes in input variables, i.e., changes in input "relative to each own component" and "relative to the

total road network (L_{tn})". The OAT analysis relative to each own component pointed out that the most sensitive parameter for the accessibility model (RNAI) is N (see **Figure 7.2a**), while for the OAT relative to the total length of road (L_{tn}) the most sensitive parameter is C (see Figure **7.2b**). Nevertheless, since each accessibility component typically has a different base value, the inputs should be added or removed using equal values to maintain fair treatment and comparison. For example, it would be unfair to compare a one per cent increase in input relative to each value, when for N component it means building 200 km of new roads, but for the C component, it means repairing 140 km of roads, and for the P component, it means upgrading 130 km of unsealed roads into sealed roads. In this case, the OAT relative to the total road network approach (L_{tn}) offers a fairer treatment because an increase of one per cent in input requires the same length of road (200km) for improvement, no matter whether roadworks are to repair (C), upgrade (P) or build the roads (N).

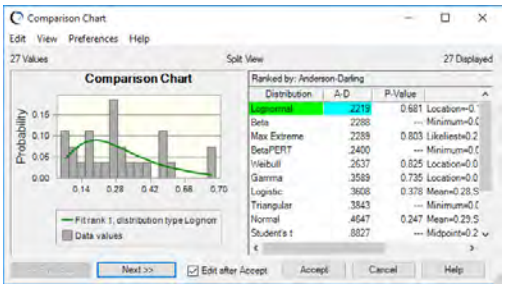
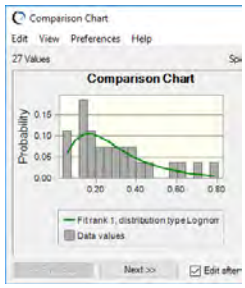
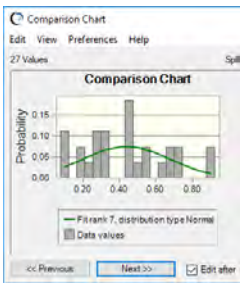
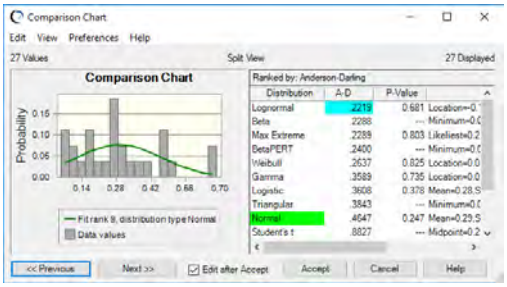
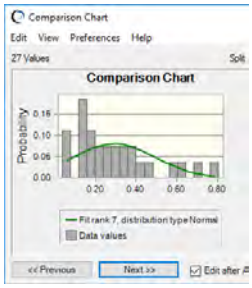
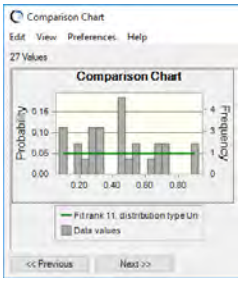
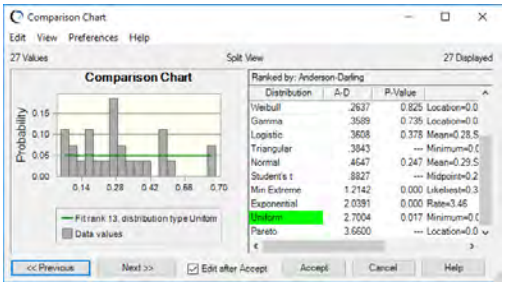
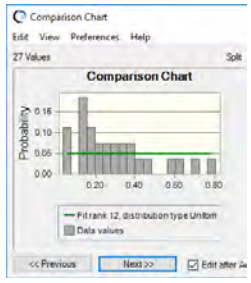
Based on the OAT sensitivity analysis as shown in **Figure 7.2b**, the results show that repairing roads in poor condition (improving C) may become a priority option to increase the overall level of accessibility because it has the most significant line gradient or elasticity value, (0.212) followed by upgrading road pavement (P), and building new roads (N).

7.2.3 Monte Carlo Simulation

Monte Carlo is a popular algorithm for generating random numbers in financial engineering, risk management, and economics analyses (Brandimarte, 2014). In the process of modelling, it is often used to simulate a combination of random values as input to a model using a global set of samples to explore the design of a model. Thus, this stochastic approach is often referred to as a global sensitivity analysis (Landau and Binder, 2015). In this research, the Monte Carlo simulation was performed using the *Crystal Ball* tool, an add-in application in Ms Excel software. The Crystal Ball tool is preferred because it is simple, fast and easy to use. In the

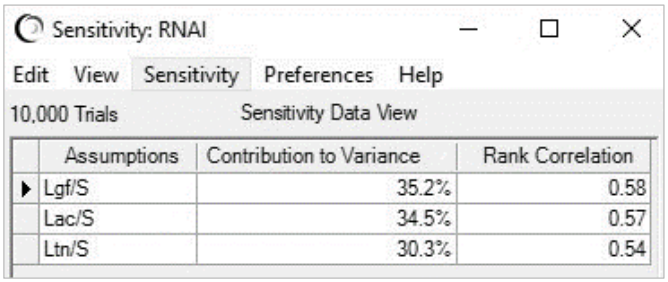
simulation, random values were generated following distributions that represent typical conditions and random variation of inputs for the accessibility components (Ltn/S, Lgf/S, and Lac/S). Based on the distribution analysis, the general distribution of accessibility components in Indonesia can be represented using several distribution models, including normal and lognormal distribution. However, the result of the distribution fit test indicated that lognormal was the best fit of distribution (see **Table 7.1**).

Table 7.1 Best fit distribution of the RNAI components using Indonesian data in the year 2014

Fit Distribution	Accessibility components		
	Network (N)	Condition (C)	Pavement (P)
Lognormal			
Normal			
Uniform (0 to 1)			

Additionally, normal and uniform distributions of accessibility components are also simulated to represent all possible changes in the input variables. The normal distribution is used to illustrates the impact when the data are normally distributed (not skewed as shown in lognormal

distribution). The uniform distribution, which was set ranging from zero to one, is used to accommodate an equal probability for each distribution value, i.e. simulating random values of accessibility components. Since the Monte Carlo algorithm generates random variables, each simulation produces different outcomes. Hence, the sensitivity analysis in this study is evaluated based on the average value from ten simulations and ten thousand trials (ten times more than the default setting) set for each run of the simulation to reduce bias assessment (see **Figure 7.3**).



Assumptions	Contribution to Variance	Rank Correlation
Lgf/S	35.2%	0.58
Lac/S	34.5%	0.57
Ltn/S	30.3%	0.54

Where: Lgf/S: condition (C); Lac/S: pavement (P); Ltn/S: network (N)

Figure 7.3 The typical output of sensitivity analysis using Monte Carlo simulation

Based on the simulation, the distribution assumption may influence the overall outcome of the accessibility index (RNAI). The simulation using lognormal and uniform distributions produce more consistent outcomes than using the normal distribution of the input variable. The MC-lognormal analysis, which uses a lognormal distribution as the inputs consistently show that N is the most sensitive parameter followed by C and P (see **Table 7.2**).

Based on the distribution of accessibility components in Indonesia, the result of MC-lognormal simulation suggested focusing on improving N component (total length of road networks) by building new roads. However, at the same time, this component has the most significant disparity value and standard deviation compared to the other components (see **Table 7.3**). For the next priority, the simulation results endorse the road managers to increase the overall accessibility level by improving (repair) the road condition (C) and upgrading the road surface

(P) from gravel road into a bituminous road. However, as the gap of contribution is not significant, i.e. less than 5% (see **Figure 7.3**), the improvement strategy in practice should be viewed case by case.

Table 7.2 Sensitivity report of Monte Carlo (MC) simulation based on distribution input

Trial Simulation	Contribution to variance (%)											
	MC-Lognormal				MC-normal				MC-uniform			
	N	C	P	Max	N	C	P	Max	N	C	P	Max
1	36.4	33.4	30.2	N	32.4	34.8	32.8	C	31.0	35.6	33.4	C
2	36.9	32.7	30.4	N	32.5	33.5	34.0	P	32.1	34.2	33.7	C
3	35.9	33.6	30.5	N	34.6	34.2	31.2	N	31.0	34.6	34.4	C
4	35.2	34.1	30.7	N	31.8	33.3	34.9	P	30.6	35.2	34.1	C
5	35.6	33.7	30.8	N	34.5	32.4	33.1	N	30.8	35.3	33.8	C
6	35.9	34.4	29.8	N	33.4	32.5	34.2	P	30.5	34.9	34.6	C
7	36.6	32.8	30.7	N	33.4	32.5	34.2	P	31.2	35.3	33.5	C
8	35.9	33.3	30.8	N	33.9	32.7	33.4	N	31.2	34.6	34.2	C
9	37.6	33.3	29.1	N	32.4	34.1	33.4	C	30.5	35.1	30.5	C
10	38.1	32.3	29.6	N	33.8	33.8	32.4	N/C	31.6	35.0	33.4	C
Mean	36.4	33.4	30.3	N	33.27	33.38	33.36	C	31.1	35.0	33.6	C
Priority Order	1	2	3	N	3	1	2	C	3	1	2	C

MC-lognormal and MC-normal are based on fit distribution test using Indonesian data in the year 2014
MC-uniform uses value ranging from zero to one and uses equal probability for each frequency of distribution.

Table 7.3 The components of accessibility measure (RNAI) in Indonesia in the year 2014

Parameter	Accessibility Components (km/sq.km area)		
	Network (N=Ltn/S)	Condition (C=Lgf/S)	Pavement (P=Lac/S)
Max	0.922	0.685	0.806
Mean	0.437	0.289	0.291
Median	0.436	0.276	0.263
Standard Deviation	0.235	0.172	0.200
Disparity (max-min)	0.85	0.63	0.77

A different result of priority order was identified when the MC simulation was run using normal and uniform distribution as the inputs. The simulation results from the MC-normal and the MC-uniform confirm the previous conclusion from the regression and OAT method, which pointed out the C component as the most sensitive parameter. This result could be because the random values which are generated by the MC simulation are limited to follow the predefined assumption of distribution. Accordingly, the MC-lognormal with a left-skewed distribution has a higher probability of generating lower values than those of the MC-lognormal, which

generates more “median” or “mean” values. In general, generating random values using the MC-uniform pattern offers a neutral treatment by giving the same probability to all possible values that can be generated. It means that according to the actual distribution pattern of accessibility components, generating random values using MC-lognormal may be suitable for illustrating the overall improvement strategy for Indonesia. The MC-normal may be suitable for typical developing countries and the MC-uniform for universal cases, including developed countries.

7.2.4 Quantification formula of the RNAI model

Another fundamental consideration for identifying the most sensitive parameter in the model is by looking back to the model’s formula. In general, the most influential parameter may be identified based on the most significant coefficient in the RNAI equation. By referring the maximum value for each component from the Indonesia data of the year 2014, the RNAI equation may be transformed as follows:

$$M_2 = \frac{1}{3} \times \left(min\left\{1, \frac{(L_{tn}/S)}{(L_{tn}/S)_{max}}\right\} + min\left\{1, \frac{(L_{gf}/S)}{(L_{gf}/S)_{max}}\right\} + min\left\{1, \frac{(L_{ac}/S)}{(L_{ac}/S)_{max}}\right\}\right)$$

$$M_2 = \frac{1}{3} \times \left(min\left\{1, \frac{N}{0.922}\right\} + min\left\{1, \frac{\mathrm{C}}{0.685}\right\} + min\left\{1, \frac{\mathrm{P}}{0.806}\right\}\right)$$

$$M_2 = \frac{1}{3} \times (min\{1, \mathrm{N} \times \mathbf{1.08}\} + min\{1, \mathrm{C} \times \mathbf{1.46}\} + min\{1, \mathrm{P} \times \mathbf{1.24}\}) \qquad \text{Equation 7.1}$$

Equation 7.1 shows that the C component is the most sensitive parameter in the RNAI model with the most significant coefficient (1.46), followed by P (1.24) and N (1.08). It should be noted that even though the RNAI model has put an equal weighting scheme in the aggregation procedure, the model still gives priority to specific components. This condition occurs because the concept of equity in the RNAI model tries to give fair treatment for each component, i.e. the value does not necessarily be in the top but should be in a balanced condition across nation. Accordingly, the existing condition of road assets and their distribution may still influence the overall strategy of how the road network accessibility is managed.

In conclusion, for general cases, the overall results of the sensitivity analyses using regression, OAT, Monte Carlo simulation and model equation (see **Table 7.4**) pointed out that repairing roads in poor condition (improving C) could become a priority option to increase the overall level of accessibility. However, as each component of the RNAI model has a unique role in supporting the development of regional accessibility, road managers should consider improving these three variables in a balanced way to achieve optimum levels of road network accessibility.

Table 7.4 The results of sensitivity analysis

Method		Priority order		
		N	C	P
Regression		3	1	2
One at a time (OAT)		3	1	2
Monte Carlo Simulation	MC-lognormal	1	2	3
	MC-normal	3	1	2
	MC-uniform	3	1	2
Model formula or equation		3	1	2

Also, as typically both developed and developing countries share the same pattern of road asset condition ($N > P > C$), based on road engineering point of view. The overall conclusions from the sensitivity analysis can be generalised and used as a universal approach for managing road network accessibility.

7.3 Scenario Analysis

In theory, it is always possible to change one parameter of an accessibility component independently. However, since managing road assets should follow some maintenance standards and strategies (Robinson et al., 1998), the available options of roadworks to improve accessibility may influence some accessibility components at a time, i.e., as one package of a roadwork project. For example, based on the road asset management perspective, it would be impractical to upgrade a “poor unsealed” road into a “poor sealed” road for representing an improvement in P when the N and C components remain constant. Although it may be possible

by updating the existing maintenance standards, the option is not feasible neither from an engineering nor an economics point of view. The standard option always recommends upgrading all conditions of unsealed roads directly into "good" sealed roads, i.e. improving P and C component simultaneously. Hence, in developing maintenance strategies to improve regional accessibility, it is better to consider the typical roadwork standards as an alternative scenario in managing road network accessibility. In this case, the scenario analysis may follow some improvement (+) and degradation (-) scenarios, as presented in **Table 7.5** and **Table 7.6**.

Table 7.5 The scenario and theoretical impacts of changes in the RNAI components

Changing in on of accessibility (RNAI) component			Impact on the RNAI [b]		
Component	Adjust	Alternative scenario	N	C	P
Network ($\boldsymbol{N}$)	(+)	[1] addition of a good new sealed road	+	+	+
		[2] addition of a good new unsealed road	+	+	n
	(-)	[3] loss of a bad sealed road	-	n	-
		[4] loss of a bad unsealed road	-	n	n
		[5] loss of a good sealed road	-	-	-
		[6] loss of a good unsealed road	-	-	n
Condition ($\boldsymbol{C}$)	(+)	[7] reparation of a poor road into a good road	n	+	n
	(-)	[8] abandonment of a bad road (do nothing)	n	-	n
Pavement ($\boldsymbol{P}$)	(+)	[9] upgrade of a bad unsealed road into a good sealed road	n	+	+
		[10] upgrade of a good-unsealed road into a good sealed road	n	n	+
	(-)	(11) downgrading of a sealed road into an unsealed road	n/a	n/a	n/a

a. (+): improvement scenario, (-): degradation scenario
b. ▭ = Direct impact (focus of changing in component), ▭ = Indirect impact; (+) = Positive impact; (-) = Negative impact; (n) = No impact; (n/a) = Not applicable. Where: N=network; C=condition; P=pavement.

Table 7.6 Scenario of changes in input for accessibility index

Improvement scenario (+)						Degradation scenario (-)					
Addition of road [a]			The new value of road asset			Reduction of road [b]			The new value of road asset		
%	(km)	(km/sq.km)	Ltn/S	Lgf/S	Lac/S	%	(km)	(km/sq.km)	Ltn/S	Lgf/S	Lac/S
+100	+21,803	+0.44	0.87	0.71	0.70	-0	-0	-0.00	0.44	0.28	0.26
+90	+19,623	+0.39	0.83	0.67	0.66	-10	-2,180	-0.04	0.39	0.23	0.22
+80	+17,442	+0.35	0.78	0.63	0.61	-20	-4,361	-0.09	0.35	0.19	0.18
+70	+15,262	+0.31	0.74	0.58	0.57	-30	-6,541	-0.13	0.31	0.15	0.13
+60	+13,082	+0.26	0.70	0.54	0.52	-40	-8,721	-0.17	0.26	0.10	0.09
+50	+10,901	+0.22	0.65	0.49	0.48	-50	-10,901	-0.22	0.22	0.06	0.04
+40	+8,721	+0.17	0.61	0.45	0.44	-60	-13,082	-0.26	0.17	0.01	0.00
+30	+6,541	+0.13	0.57	0.41	0.39	-70	-15,262	-0.31	0.13	-0.03 [c]	-0.04 [c]
+20	+4,361	+0.09	0.52	0.36	0.35	-80	-17,442	-0.35	0.09	-0.07[c]	-0.09 [c]
+10	+2,180	+0.04	0.48	0.32	0.31	-90	-19,623	-0.39	0.04	-0.12[c]	-0.13 [c]
+0	+0	+0.00	0.44	0.28	0.26	-100	-21,803	-0.44	0.00	-0.16[c]	-0.17 [c]

a. The number of road assets that should be improved; b. number of road asset that should be reduced or degraded.
c. Not applicable because the minimum value of road density is zero. The base case scenario is using the median value of accessibility in Indonesia with the unit area is set to be 50.000 sq. km to represent the mean value of the provincial area.

As illustrated in **Table 7.5**, the changes in scenarios of accessibility components (N, C, and P) may be broadly divided into improvement and degradation. Improvement is based on roadwork schemes from maintenance standards, and degradation relates to reductions or loss of road access due to natural disasters, extreme weather impacts, road accidents, or lack of maintenance budget. For the development scenario, the routine and periodic maintenance is represented by scenario [7], road improvement (upgrade) by scenario [9] and [10], and road development by scenario [1] and [2].

In general, similar to the OAT analysis chart, the more sensitive scenario may be identified from the higher gradient of impact line. Based on the scenario analysis (see **Figure 7.4**), the results pointed out that the most sensitive scenario were the changes in good sealed-roads, by either improving and adding new roads (scenario 1) or degrading the roads, e.g., road cut due to landslide or earthquake (scenario 5). It might happen because both scenarios not only affect the N component but also the other accessibility components at the same time, i.e. C and P (see **Table 7.5**, **Table 7.7**, and **Table 7.8**).

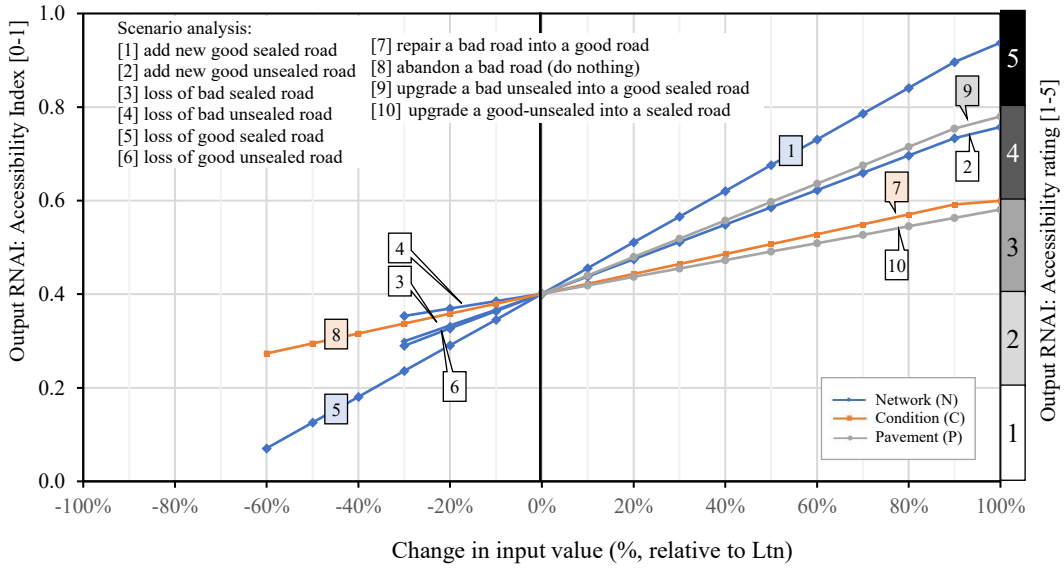


Figure 7.4 The impact of change in accessibility component using scenario analysis

Table 7.7 Road management impact on accessibility (RNAI)

Impact rank [a]	Improvement Scenario	Component [b]	
		Main	Secondary
1	[1] add new good sealed road	N	C, P
2	[9] upgrade a bad unsealed road into a good sealed road	P	C
3	[2] add new good unsealed road	N	C
4	[7] repair a bad road into a good road	C	n/a
5	[10] upgrade a good-unsealed into a good sealed road	P	n/a

a. Ranking: 1=highest impact; 5=lowest impact.
b. N=network; C=condition; P=pavement; n/a=not applicable

Table 7.8 Road degradation impact on accessibility (RNAI)

Impact rank [a]	Degradation Scenario	Component [b]		Example
		Main	Secondary	
1	[5] loss of a good sealed road	N	C, P	Road segment is cut or blocked due to extreme weather events (EWE), disaster, or road accidents.
2	[6] loss of a good unsealed road	N	C	
3	[3] loss of a bad sealed road	N	P	
4	[8] abandon bad road (do nothing)	C	n/a	Abandon some roads within the road network without maintenance due to a lack of budget.
	[11] downgrade a sealed road into an unsealed road	P	n/a	
5	[4] loss of a bad unsealed road	N	n/a	

a. Ranking: 1=highest impact; 5=lowest impact.
b. N=network; C=condition; P=pavement; n/a=not applicable

In terms of the improvement scenario, the scenario to build new roads was initially expected to be the most sensitive because it requires the most significant investment of effort, time, and money compared to the other scenarios. Subsequently, ‘upgrade bad unsealed road into a good sealed road’ become the second important scenario followed by ‘add a new unsealed road,’ ‘repair bad road into a good road’ and ‘upgrade good-unsealed into a good-sealed road.’

In terms of the degradation scenario, the result shows that the accessibility level decreases significantly when a road segment is cut or blocked due to EWEs, disasters, or road accidents. These events are followed by the scenario of ignoring the road asset or not performing maintenance due to lack of budget (see **Table 7.8**). These results of scenario analysis are theoretically accepted because when a road is blocked or cut, it means that the road access is lost. Since a good sealed road typically serves a high traffic volume, the degradation or cutting off access to this road category has a more significant impact on the overall performance of the

road network, e.g. congestion and increased costs both for road users (RUC) and agencies (RAC).

Overall, the scenario analysis pointed out that the higher the investment made in road asset management, the greater the improvement is to accessibility. This result supports previous literature reviews. Although the results from the scenario analysis sound theoretically correct, since the analyses only consider the engineering aspect, those scenarios still need to be economically assessed to ensure their effectiveness by considering the life cycle costs and budget constraints. The economic-based analysis for the improvement and degradation scenarios are presented in **Chapter 8**.

7.4 Summary

This chapter presents the sensitivity and scenario analyses for the RNAI model. Both analyses share a similar concept by predicting outcomes given in certain situations. The difference is that sensitivity analysis focuses on the changes in input variable based on the theoretical aspect (paper-based). In contrast, scenario analysis evaluates changes in several inputs at the same time according to specific settings and circumstances that are most likely to occur, i.e. it focuses on the practical aspect. Based on the results of sensitivity analysis, the most sensitive parameter in the RNAI model is road condition (C) followed by pavement type (P), and road network (N). However, as each component in the RNAI model may have a unique role in supporting the development of regional accessibility, road managers should consider improving these three variables in a balanced way to achieve the optimum level of road network accessibility, i.e. the improvements to strategies in practice should be viewed case by case.

In terms of scenario analysis, the analysis offers a more realistic picture of application for the RNAI model than the sensitivity analysis as it reflects the general scheme of conditions and circumstances in road asset management. The scenario analysis proves that roadwork standards

influence various components of accessibility at the same time. The overall result pointed out that the higher investment made in road asset management, the more significant the improvement of accessibility is. Although the results sound theoretically correct, since the analyses only consider the engineering aspect, the scenarios still need to be economically assessed by considering the life cycle costs and budget constraints to ensure the cost-effectiveness. Further economic assessment may be seen in the next chapter, **Chapter 8**.

CHAPTER 8

MODEL APPLICATION: DEVELOPING STANDARDS AND STRATEGIES TO MANAGE ROAD NETWORKS ACCESSIBILITY

8.1 Introduction

This chapter presents an economic assessment on the overall technical approach and scenarios of accessibility management described in **Chapter 7**, e.g. sensitivity and scenario analysis. The assessment aims to ensure the cost-effectiveness from the proposed standards and strategies of accessibility management and answer the research question on how accessibility should be managed under climate change or extreme weather conditions. Furthermore, the impact of budget constraints on accessibility levels is also presented.

This chapter consists of eight sections. First, it describes the approach to link the accessibility model (RNAI) with a road asset management scheme using HDM-4. The characteristics of Kalimantan province as the case study are presented and used to justify the impact of road maintenance regime, climate change and extreme weather conditions on accessibility. As the countermeasure, adaptation standards and strategies are also proposed to manage accessibility under such conditions.

8.2 Linking Accessibility Model with Road Asset Management Tool (HDM-4)

In general, accessibility and road asset management (RAM) share similar aims, i.e. to provide optimal performance of road networks and ensure the roads are always open in-service throughout the year. The RAM focuses on road conditions and puts more weight on traffic to improve cost-effectiveness. In contrast, accessibility focuses on equity to improve the availability, quality, and reliability of road performance without directly considering aspects of

traffic management. Although the assessment methods are different, there is a strong possibility for integration because both use road infrastructure features as indicators in assessing their performance. By building a link between the RNAI model and RAM using HDM-4 tool, the economic appraisal in RAM can be utilized to assess and simulate the long-term impact of accessibility management scenarios on the budget requirement and the overall road conditions during its economic life. This integration can be used as an innovation in the current appraisal of road asset management.

In practice, the integration with HDM-4 is performed by using the components of accessibility model (RNAI), i.e. road length, type of pavement and roughness, as inputs in the HDM-4 tool. Once the HDM-4 has been successfully executed, it generates the annual value for each accessibility component as the output, and the new RNAI value can be annually calculated (see **Figure 8.1**). The new RNAI is used to compare and assess the impact of various accessibility management scenarios, including base scenarios, on accessibility performance. Also, it ensures that adaptation scenarios meet the predefined target of accessibility and budget targets.

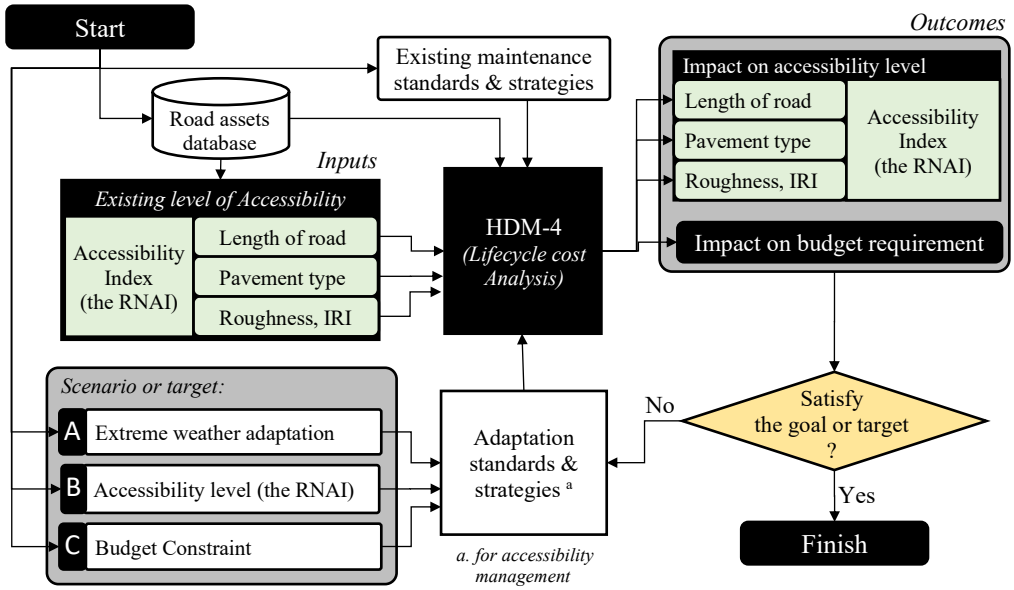


Figure 8.1 Framework to link the RNAI model with HDM-4

8.3 Road Asset Database

8.3.1 Profile of Kalimantan Selatan Province

Kalimantan Selatan (Kalsel) is a province in Indonesia located on Kalimantan Island (Borneo) with Banjarmasin as the capital (see **Figure 8.2**). Inhabited by 101.2 population per square km, Kalsel is the most populated province located on the islands of Borneo (BPS-Statistics, 2017).



Figure 8.2 Kalimantan Selatan Province (after Pta-banjarmasin, 2018)

Concerning the transportation sector, although a region has an excellent value of road density, the perceived accessibility level remains low because the road pavements are typically in poor condition. For instance, in Kalimantan, it can take up to four hours to travel 180 km by road (Simorangkir, 2017). In practice, road users encounter 30 km of good asphalt roads, 70 km of

bad asphalt roads, 50 km of bad gravel roads, and 30 km of earth roads, where conditions worsen during the rainy season. Accordingly, rather than travelling at a reasonable speed (80 km/h), road users are often forced to drive slowly (15 km/h) as they travel along poor and unpaved roads. This example highlights the gap in the minimum standards of road performance between developing and developed countries. In developing countries, since gravel and earth road network are still prevalent, road performance suffers as a result. Thus, based on the RNAI model (see **Table 6.8** in **Chapter 6.2.4**), Kalsel province, which has a limited road network, along with partially unsealed roads and roads in poor condition, is a region with low level of accessibility (RNAI= 0.31). There are significant restrictions of access to a wide range of services and opportunities in Kalsel province. Also, the area has limited route options, and road surfaces are partly unsealed, which renders them unusable at certain times of the year.

8.3.2 Road Asset in the Kalimantan Selatan Province

The Kalimantan Selatan province has 12,518 km road asset, of which 37.9% are still unsealed (see **Figure 8.3**). The distribution of roads based on traffic and condition in 2014 is shown in **Table 8.1** This table acts representative matrix used in the case study to simulate the impact of climate change and extreme weather events (EWEs) on the overall road condition and accessibility level. The maintenance standards and strategies follow the Indonesian maintenance standards (IRMS). Further information about the IRMS standards can be seen in **Appendix B**.

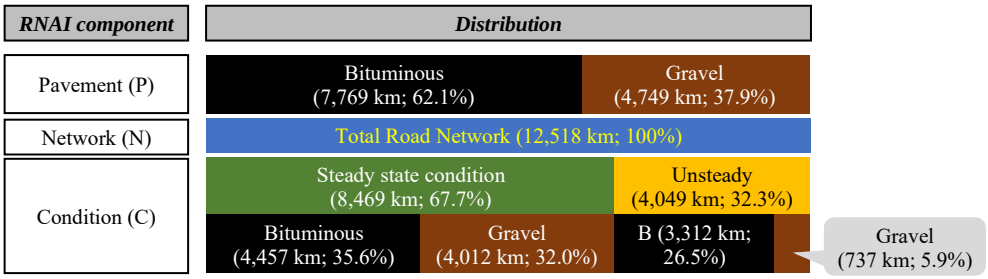


Figure 8.3 Distribution of road category in Kalimantan Selatan Province in 2014

Table 8.1 Categorized length of the road network
in Kalimantan Selatan province in the year 2014 (km)

Surface Type	Road status	Traffic Category	Condition [a]				Total
			Good	Fair	Poor	Bad	
Bituminous (Asphalt)	National	[T1] High	231	16	-	-	247
		[T2] Medium	531	42	10	-	583
		[T3] Low	326	24	4	3	357
	Provincial	[T1] High	28	12	15	10	65
		[T2] Medium	184	96	24	14	318
		[T3] Low	146	61	55	56	318
	Regency/ District	[T1] High	494	387	53	24	958
		[T2] Medium	675	519	984	874	3,052
		[T3] Low	462	223	753	433	1,871
Unsealed (Gravel)	National	[T5] Medium	12	5	-	-	17
		[T6] Low	-	-	-	-	-
	Provincial	[T5] Medium	52	33	22	-	107
		[T6] Low	35	6	3	-	44
	Regency/ District	[T5] Medium	1,470	651	154	122	2,397
		[T6] Low	1,092	656	187	249	2,184
		Total Road Asset	5,738	2,731	2,264	1,785	12,518

a. based on the Indonesian Ministry of Public Works (2015) in BPS (2015)

8.4 The Impacts of Road Asset Management Regime on Accessibility (Unconstrained Budget Scenario)

8.4.1 Optimisation Method in the HDM-4

In the HDM-4 lifecycle cost analysis, road networks can be optimised using three methods, i.e., maximise NPV (Net Present Value), maximise dIRI (minimising average roughness), and minimise cost for target IRI (Odoki and Kerali, 2000). However, in practice, max-NPV and max-dIRI methods are more popular as they let the system optimise equally without external interference. Both methods use NPV/cost to justify the investment decision. However, in practice, the max-dIRI method always requests similar or slightly higher budgets than max-NPV because the main objective is to reach a minimum level of roughness (Cafiso et al., 2002). As illustrated in **Figure 8.4** and **Figure 8.5,** using Kalsel province as a case study, the simulation results confirmed that max-NPV and max-dIRI generated an almost similar result of

road condition and accessibility level for twenty years of analysis. This pattern occurred in both the Minimum (DM) and IRMS scenarios.

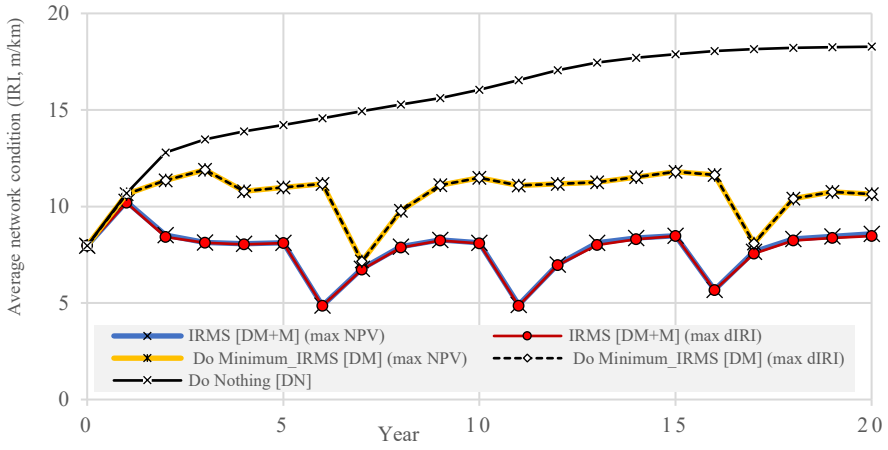


Figure 8.4 Road network condition Vs HDM-4 optimisation method (unconstrained budget)

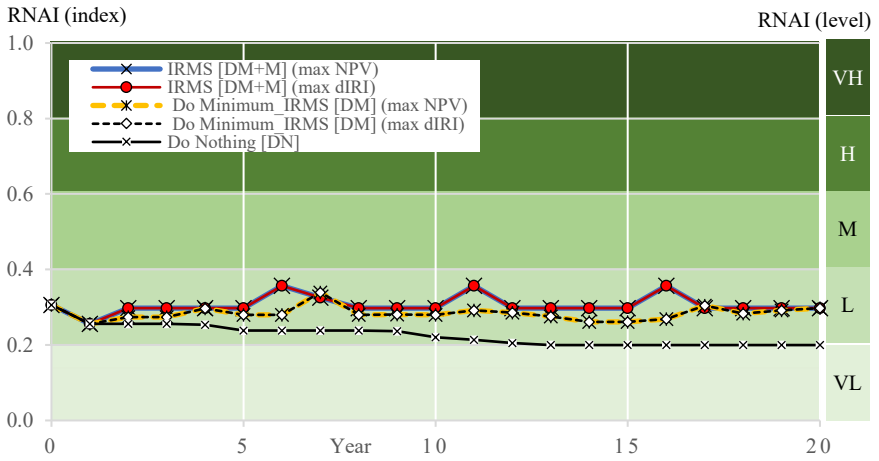


Figure 8.5 Accessibility Vs HDM-4 optimisation methods (unconstrained budget)

In the more detailed results, although the max-dIRI method gives a slightly better road condition with a low increase in the budget requirement, because the difference is not significant, the two methods produce the same level of accessibility (see **Table 8.2)**. It indicates that the current Indonesian maintenance standards (IRMS) are quite useful in optimising the condition of the road network for the NPV or dIRI. Nevertheless, because accessibility management requests

that roads should always be in steady-state conditions, the max-dIRI method which aims to minimise the average roughness condition is theoretically more relevant to the concept and objectives of accessibility management. Thus, the accessibility management scenarios in this research are simulated using the max-dIRI optimisation method.

Table 8.2 Road conditions and budget requirement based on HDM-4 optimisation methods

Parameter		The scenario of maintenance standards and optimisation method				
		Do Nothing (DN)	Do Minimum [DM] [a]		Maintenance [M] [b]	
			max NPV	max dIRI	max NPV	max dIRI
Average roughness (IRI, m/km)	The first 5-years	13.01	11.13	11.13	8.62	8.58
	20 years periods	15.95	10.74	10.74	7.73	7.68
Budget requirement (billion IDR)	The first 5-years	n/a	18,148.9	18,148.9	27,671.5	27,672.7
	20 years periods	n/a	48,288.4	48,288.4	54,086.3	55,322.3

a. Do minimum [DM] = IRMS routine maintenance and reconstruction.
b Maintenance [M]: IRMS routine and periodic maintenance.

8.4.2 Life Cycle Cost Analysis (LCCA) on Accessibility Improvement Scenarios

This section evaluates the impact of an engineering-based scenario of accessibility improvement that has been elaborated in **Chapter 7** using life cycle cost analysis (LCCA) as part of economic appraisal in road asset management. The analysis will use 'do minimum' and the IRMS standards as the base maintenance option, i.e. the base option is utilised when no specific scenario is reserved.

8.4.2.1 Do Minimum scenario as the base maintenance options

In general, although it may not be practical, the Do Minimum scenario was applied to represent the scenario of accessibility development in **Chapter 7**. Based on the HDM-4 simulation, the results pointed out that strategy for increasing accessibility level from low (L) to the top-level (VH) is only achieved by building a new road(s), i.e. scenario [01c] (see **Figure 8.6**). Although the new road(s) may be constructed using any type of road surface, the LCCA indicated that building a sealed road has a better impact on improving accessibility. By doubling the existing length of the road network (constructing new roads) using bituminous pavement, the

accessibility level can increase by two steps (e.g. from low into high level). While constructing it in the form of gravel pavement results in a one-level increase, e.g. from low (L) to medium (M) accessibility.

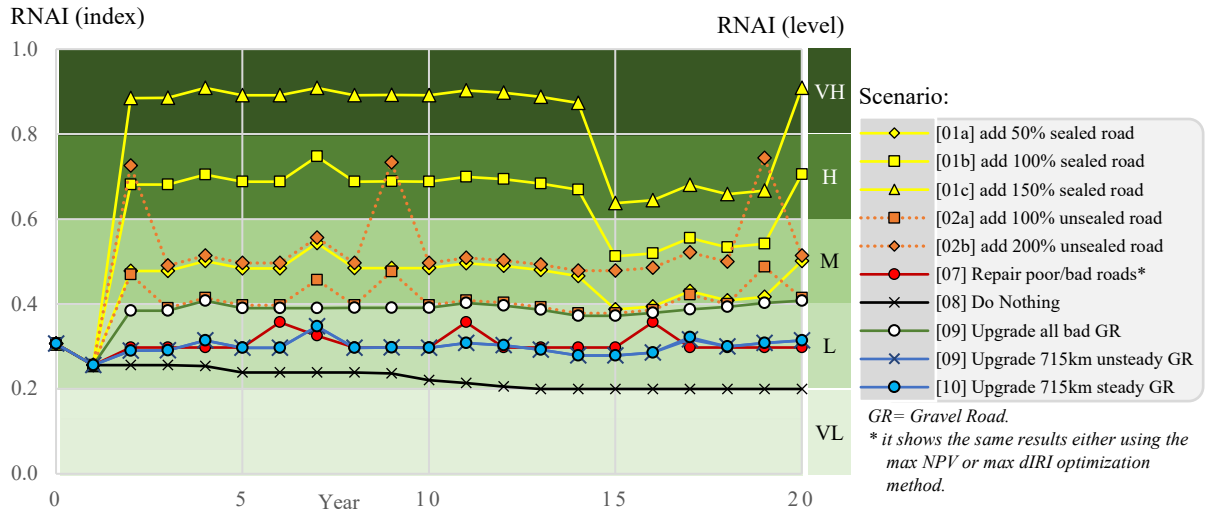


Figure 8.6 Accessibility improvement using Do Minimum as the base option (based on the sensitivity analysis scenario in Table 7.5, Chapter 7.3)

In terms of the upgrading scenario, there is no significant difference in accessibility outcomes when the scenario to upgrade 715 km of gravel roads is applied either in unsteady (scenario [09]) or in steady-state (scenario [10]) condition of gravel roads. This may occur because all the steady-state gravel road in 2014 was in an unsteady-state (poor or bad) by 2015 due to lack of maintenance. For instance, the preservation budget was cut and instead, it was used to upgrade gravel roads or build a new road(s). This result indicates that the overall road networks condition cannot be abandon without maintenance. The condition of road infrastructures still needs to be preserved and managed. Thus, the option to use a preservation scheme (routine and periodic maintenance) as the base option of road maintenance is crucial and mandatory.

8.4.2.2 The IRMS maintenance as the base maintenance options

This scenario aims to show the practicality aspect of accessibility development scenario when the roads are maintained using IRMS maintenance standards. Based on the simulation, the

results indicate that the implementation of IRMS standards increases accessibility and reduces the requirement to build new roads by 40% (see **Figure 8.7** and **Figure 8.8**) by increasing the accessibility level from low (L) to high (H).

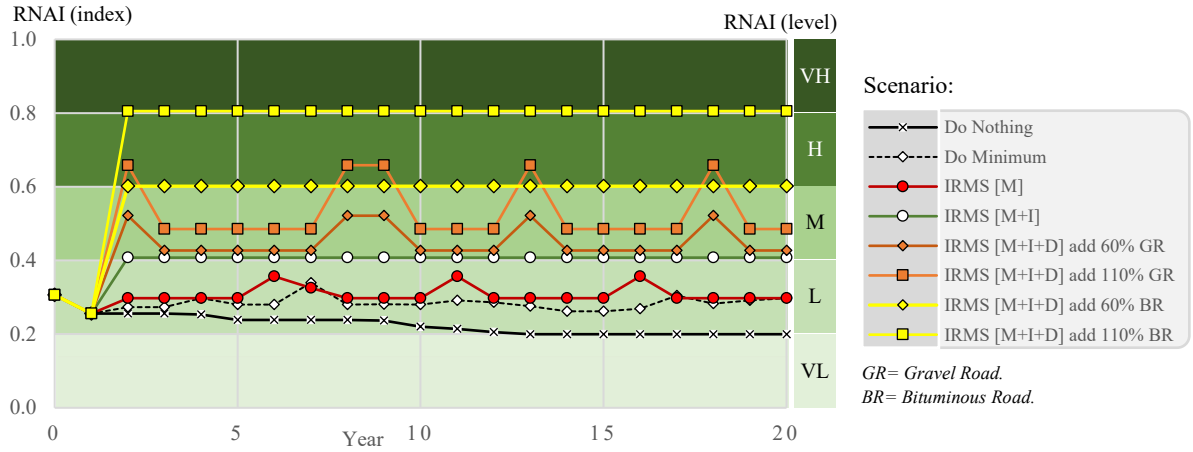


Figure 8.7 Accessibility development using IRMS standards as the base options

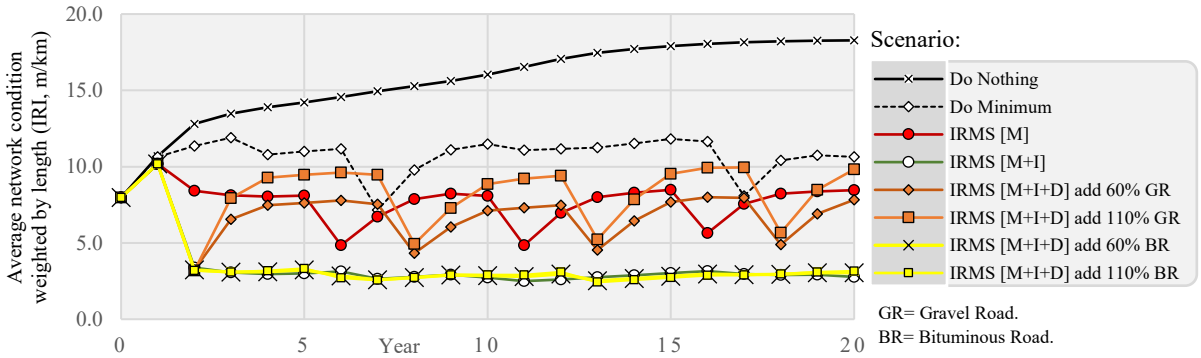


Figure 8.8 Road condition Vs Scenario of accessibility development using IRMS standards as the base options (unconstrained budget)

8.4.3 Accessibility Management by Optimising the Existing Road Assets

8.4.3.1 Accessibility management based on existing Indonesian maintenance standards

Budget is typical issue for managing road assets in developing countries (Chinowsky et al., 2015). Inadequate budgets for investment in the transport sector limit the options and strategies for road mangers to increase the level of accessibility. Low budgets make it hard for local governments to build new roads without subsidies or an individual budget allocation from the

central government. Accordingly, this section tries to find out how accessibility can be optimised using the current road assets, i.e. without building a new road(s) or segment(s), to minimise the road agency cost (RAC).

In terms of optimising accessibility level using current road assets, the scenario to upgrade gravel roads become bituminous roads was found to be the most promising option to raise the accessibility level (see **Chapter 8.4.2**). However, the upgrading scenario should not be executed simultaneously for all gravel road segments within the first year. However, it should be done in stages, e.g. gradually upgrade during the first five-years of analysis. This staging strategy is designed not only to address budgeting issues but also to minimise the impact to traffic by not fully closing road access during the construction period.

Initially, the upgrade priority is given to gravel roads in poor or bad condition. Because the gravel roads that are in bad condition essentially need to be re-gravelled, the roadwork budget for re-gravelling may be shifted as an extra budget for upgrading the roads into bituminous roads. Thus, the budget can be optimised not only for repairing the roads condition but also for upgrading the roads pavement simultaneously. In Kalsel province, the scenarios and priority for upgrading the gravel roads are illustrated in **Table 8.3**. The gravel roads are planned to be upgraded gradually within five years (Y1-Y5) starting with the bad roads before upgrading the good roads.

Table 8.3 Scenario of a gradual upgrade of gravel roads in the Kalimantan Selatan province

a) The existing distribution of road assets

Road status	Traffic Category	Road length based on condition (km)				
		Good	Fair	Poor	Bad	Total
National	[T5]	12	5	-	-	17
	[6] Low	-	-	-	-	-
Provincial	[T5]	52	33	22	-	107
	[6] Low	35	6	3	-	44
Regency/ Municipal	[T5]	1,470	651	154	122	2,397
	[6] Low	1,092	656	187	249	2,184
Grand Total		2,661	1,351	366	371	4,749

b) Priority order for upgrade

Phase [a] (priority)	Length (km)	Condition in 2014 (Y0)
Y1 (2015)	737	Poor/Bad
Y2 (2016)	794	Fair
Y3 (2017)	656	Fair
Y4 (2018)	1,470	Good
Y5 (2019)	1,092	Good

a. Y1= PGT5R3, PGT6R3, RGT5R3, RGT5R4, RGT6R3, RGT5R4; Y2= RGT5R2, PGT6R2, PGT5R2, NGT2R2, NGT1R1, PGT5R1, PGT6R1; Y3= RGT6R2; Y4= RGT5R1; Y5= RGT6R1.

Based on the HDM-4 analysis, **Figure 8.9** shows that accessibility only rises from a low level (L) into a medium level (M) by upgrading the gravel roads into bituminous roads. When the budget is limited, the option to gradually upgrade within the initial five years is a promising option because it successfully raises accessibility from low to medium level. Meanwhile, when road preservation scenarios (routine and periodic maintenance of IRMS standards) are applied, the accessibility level remains the same (L, low level) during 20 years of analysis. However, there is a temporary improvement in road condition (roughness) once in five years due to the periodic maintenance.

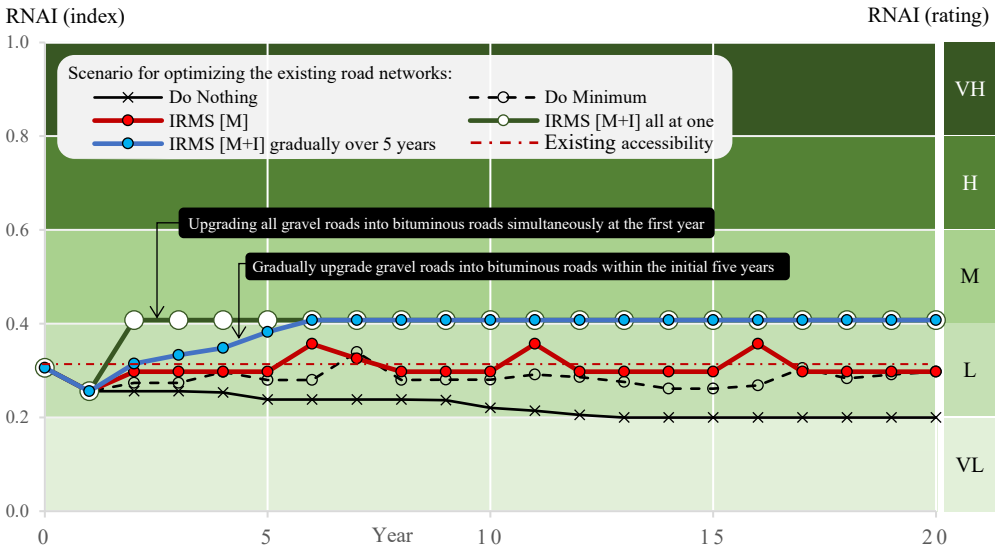


Figure 8.9 Accessibility optimisation scenarios using the existing road asset

As can be identified from **Figure 8.10**, because there are no changes in the length of road and type of pavement (component N and P remain the same) the fluctuation in accessibility level (red line, IRMS [M] in **Figure 8.9**) should be caused by the fluctuation in the roads condition component (C). When elaborated in more detail, it was apparently caused by a sudden improvement in gravel roads condition due to re-gravelling roadworks. The bituminous roads remained constant during twenty years period of analysis (see **Figure 8.11a**). This fact indicates

that the IRMS standards for bituminous roads seem adequate to sustain the current level of accessibility, but the maintenance standards for gravel roads need to be reviewed. As an alternative, upgrading gravel roads into bituminous roads within five years may avoid the issue of gravel road maintenance standards and dramatically increase the overall performance of the road network over twenty years (see **Figure 8.11b**).

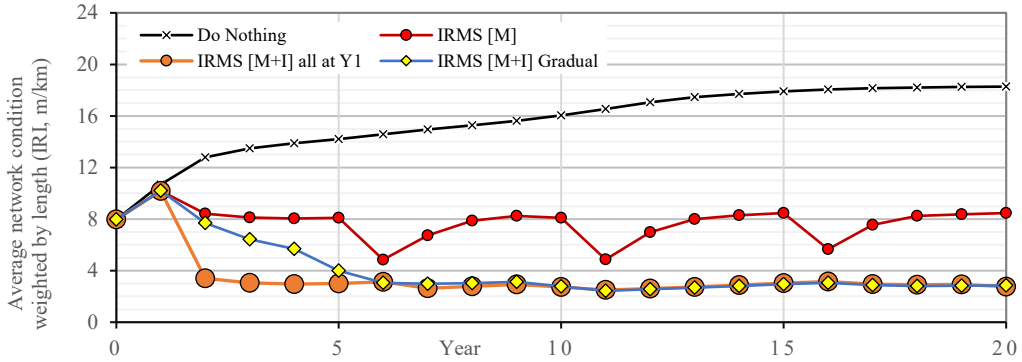
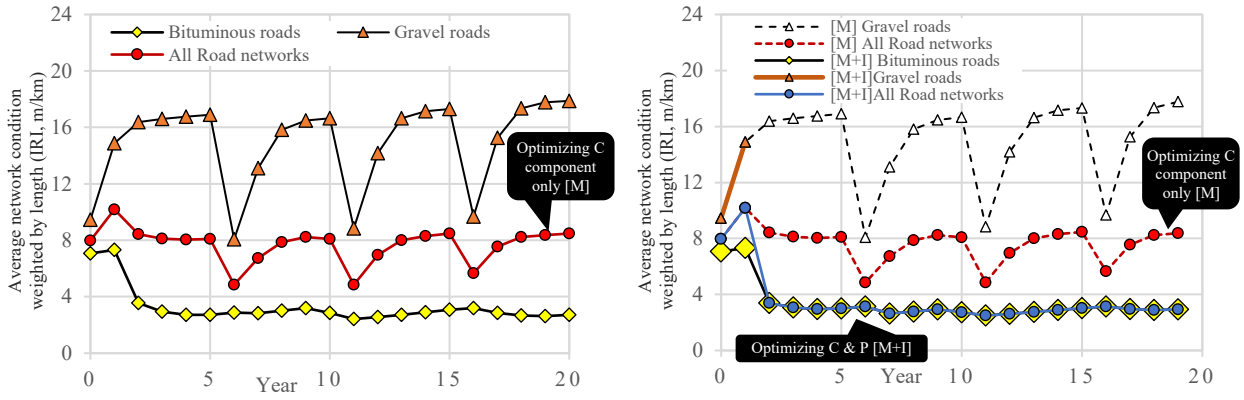


Figure 8.10 Road network condition using existing IRMS maintenance standards



a. IRMS maintenance [M]

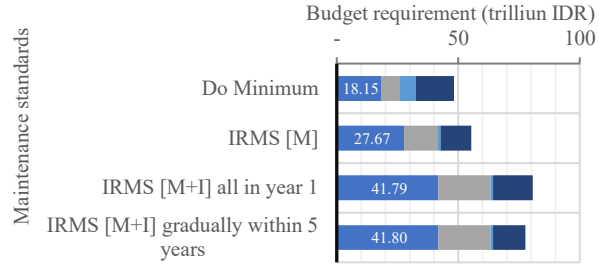
b. IRMS maintenance and upgrade [M+I]

Figure 8.11 Road network condition based on surface class

8.4.3.2 The budget requirement for optimising accessibility using the existing road networks

In terms of budget requirement, the trade-off between improvements to accessibility and the cost of investment indicates that road networks in Kalsel should be managed using IRMS maintenance standards. Based on **Figure 8.12**, the IRMS standards can sustain the current

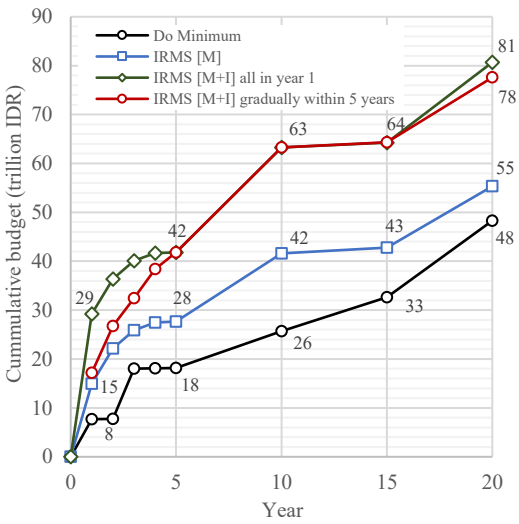
accessibility level with a 55 trillion IDR or 14.5% increase in the budget compared to the do minimum (DM) scenario. For enhancing the accessibility level from low to the average level using IRMS [M+I] scenario, road managers in Kalsel province should provide 78 trillion IDR or a 41.8% budget increase for the preservation scheme (IRMS [M]) which would upgrade gravel roads to bituminous roads.



Budgeting Period	Do Minimum	IRMS [M]	IRMS [M+I]	
			all in year1[a]	Staging [b]
Y1-Y5	18.1	27.7	41.8	41.8
Y6-Y10	7.5	13.9	21.5	21.5
Y 11-Y16	6.9	1.1	1.0	1.0
Y15-Y20	15.7	12.6	16.4	13.3
Total in 20 years	48	55	81	78

a. all upgrade was done in the year 1 simultaneously;
b. gradually upgrades within the first 5-year period.

a.Budget requirement every 5 year



b. Cumulative budget over 20 years

Figure 8.12 Budget requirement Vs Road maintenance scenarios (unconstrained budget)

Based on an unconstrained budget simulation, the budget requirement in Y10-Y15 was found to be very low, which could be due to significant investment in the first year of analysis to upgrade roads from gravel to bituminous roads. As the pavement design standard in Indonesia is set to have a minimum of ten years of life, this can be extended by five years, rehabilitation work can be avoided by implementing periodic maintenance. It is confirmed from **Figure 8.12a** that the required budget in Y10-Y15 was meagre, but that for Y16-Y20 it increases dramatically because of periodic maintenance costs. There could also be problems with the gravel road maintenance standards (IRMS), which could explain the increase. **Figure 8.12a** shows that the

distribution of budgets was more balanced when the simulation was performed using the do minimum (DM) scenario rather than using the IRMS standard.

In application, because budget is limited, a scenario to constrain the budget requirement may be considered by road manager to distribute the budget in a more balanced way. As alternative scenarios, road managers could enhance accessibility levels by building new road segments between Y10-Y15, or by adding a scenario about climate change and the occurrence of extreme events (EWEs) to their planning. However, all these scenarios should be economically assessed and compared using the HDM-4 as the standard decision support tool to get an optimum level of accessibility under varying budget scenarios. The HDM-4 simulations using the scenario of a constrained budget are presented and elaborated in more detail in **Chapter 8.5** (e.g. **Figure 8.14**), scenarios of climate change in **Chapter 8.6** (e.g. **Figure 8.18**), and scenario of extreme weather in **Chapter 8.7** (e.g. **Figure 8.21**).

Although adding scenarios in the HDM-4 simulation increases the workload, it provides additional information about how the potential road conditions for different budget scenarios, climate change, and extreme weather events (EWEs). When the budget is limited and hard to adjust, road managers could develop adaptation standards and strategies to anticipate such scenarios.

8.4.4 The Overall Picture of Accessibility Development in Kalimantan Selatan Province

Based on the simulation of various accessibility management scenarios, the overall results indicated that accessibility in Kalimantan Selatan (Kalsel) province should be initially enhanced by optimising the existing networks, i.e., applying routine and periodic maintenance followed by upgrading gravel roads into a bituminous roads (see the orange and blue triangle in **Figure 8.13**). However, since the road length in the province is still limited (road density=0.32 km/sq.km area), the only option for enhancing the exiting network is by constructing new roads.

As the road asset management goal is to improve the level of access and reduce the remoteness of some areas, the road project should not widen or double the existing roads because this only increases capacity rather than accessibility. Therefore, the new road(s) should be constructed to connect isolated areas (districts, subdistricts, villages) or act as alternative routes for road segments that are susceptible to weather events or disasters, e.g. landslides, floods. In this case, the new road will not only improve accessibility levels but also improve the reliability of access for the whole year.

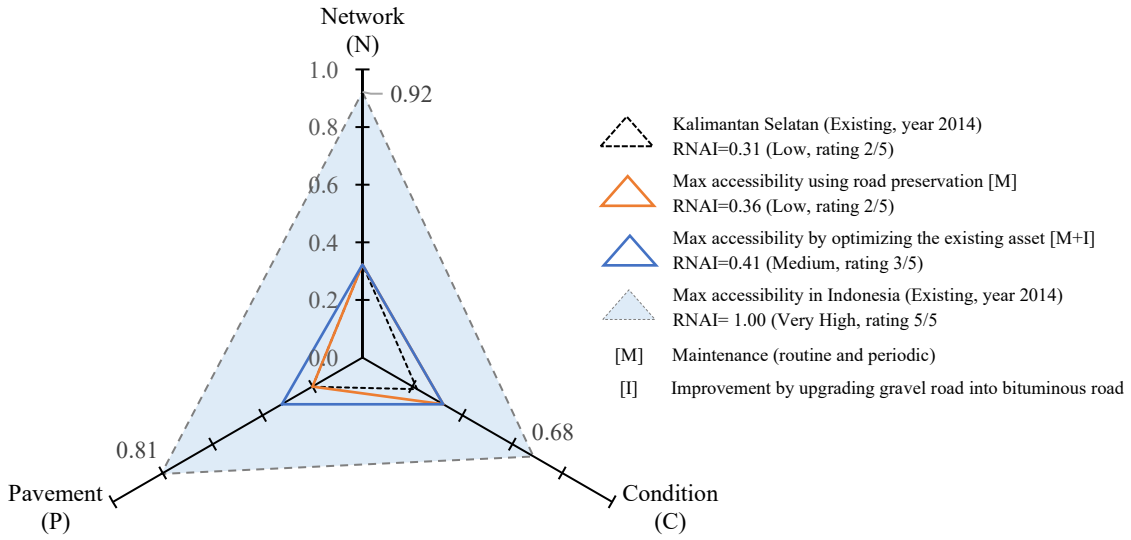


Figure 8.13 The impact of road asset management regime on the accessibility components

8.5 The Impacts of Budget Scenario on Road Condition and Accessibility

The HDM-4 simulation analysis in **Chapter 8.4** shows that the higher the accessibility target, the higher the required budget is for road maintenance and development. In the Kalimantan Selatan province, there is a need for 41,787 billion IDR to be invested for the first five-years to optimise accessibility level using current road assets (see **Table 8.4**). However, 70% of the (29.2 trillion IDR) budget should be spent in the first year of analysis. It means that more than half the budget is necessary for clearing the road maintenance backlog, extraordinary roadworks required to restore the road network to its predetermined condition so that a steady-state of road

maintenance is possible (Evdorides, 2012). However, as the availability of the budget may be limited, the constrained budget scenario should be simulated to illustrate the impact of budget constraint on accessibility level during the analysis period.

Table 8.4 Constrained budget scenario using the IRMS standards [M+I]

Code	Budget Scenario [a]	Unconstrained Budget [b]	Constrained Budget		
			High (100%)	Medium (75%)	Low (50%)
F	First year (Y1)	29,206	30,000 [c]	22,500 [c]	15,000 [c]
C	Cumulative budget during the first 5-years	41,787	n/a	n/a	n/a
A	Annual Budget during the first 5-year	n/a	10,000	7,500	5,000

a. The budget scenario: Y1 to Y5 is constrained, Y6 to Y20 is unconstrained; Yn=Year n, n=1,2,…20; n/a=not applicable.
b. Budget requirement using IRMS standards [M+I] under unconstrained budget
c. The budget scenario for Y2 to Y5 is using a medium level of the annual budget (7,500) and the budget for Y6 is unconstrained.

The scenario assumes that the budget could be constrained as high (100%), medium (75%) and low (50%) relative to the unconstrained budget requirement. Since the first-year analysis requests a massive budget, the first-year budget is also constrained. For instance, scenario F3, the first-year analysis is constrained by 50% with the subsequent annual budget-constrained at 7.5 trillion IDR. A more detail description of the budget scenario can be seen in **Table 8.5**.

Table 8.5 The scenario of a constrained budget

Budget Scenario			Constrained Budget (Trillion IDR) [a]				
Category	Level	Code	Y1	Y2	Y3	Y4	Y5
First year	High	F1	30	7.5	7.5	7.5	7.5
	Medium	F2	22.5	7.5	7.5	7.5	7.5
	Low	F3	15	7.5	7.5	7.5	7.5
Annual	High	A1	10	10	10	10	10
	Medium	A2	7.5	7.5	7.5	7.5	7.5
	Low	A3	5	5	5	5	5

a. The budget for year 6 to year 20 (Y6-Y20) is unconstrained

Based on the HDM-4 analysis (see **Figure 8.14** and **Figure 8.15**), the results show that accessibility cannot be enhanced to the upper level without the maximum budget being allocated because some gravel roads may be inaccessible during the rainy season. However, if

the aim is to sustain the current accessibility level, the low annual budget scenario (P3) may be adequate. This low budget scenario does not mean the budget is low. However, it appears that way because it is compared to the maximum cumulative unconstrained budget scenario, i.e. budget for IRMS maintenance and upgrading gravel roads to bituminous (IRMS [M]+[I]). Thus, an adequate budget is still required to ensure the implementation of IRMS maintenance standards, i.e. routine and periodic maintenance (IRMS [M]).

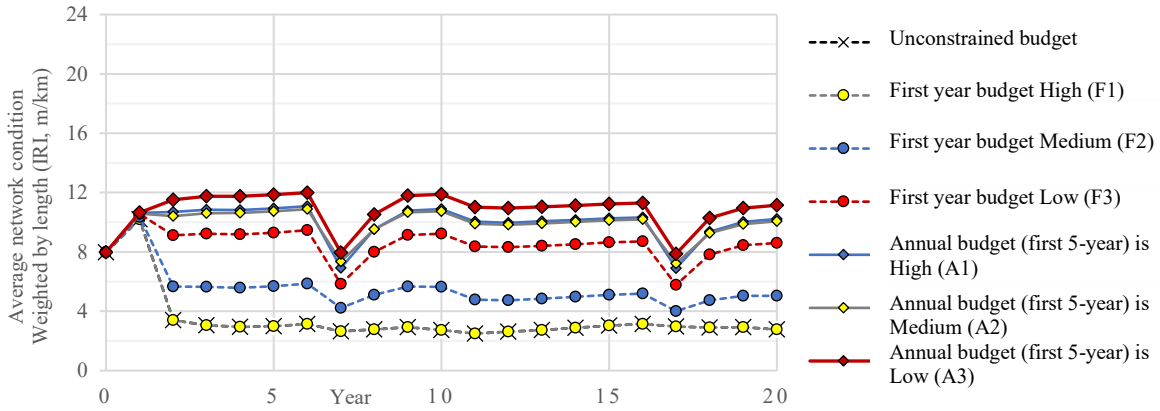


Figure 8.14 Road condition Vs budget constraint by optimising the existing road assets

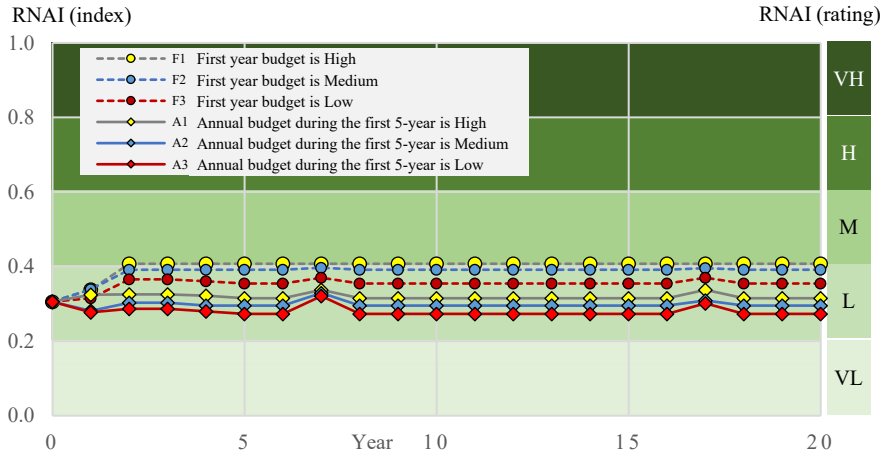


Figure 8.15 Accessibility Vs Budget constraint by optimising the existing road assets

8.6 The Impact of Climate Change on Accessibility

Based on the climate change projection in **Chapter 4**, the scenarios for changes in the climate parameter in Indonesia are broadly categorised based on the likelihood of occurrence, as shown in **Table 8.6.**

Table 8.6 Climate change scenario

Scenario		Temperature (^{0}C)	Precipitation (mm/month)	Probability [a]
Existing	EXT	27	200	100% sure
Climate change	CC1	28	250	Likely to happened
	CC2	30	300	less likely
	CC3	30	600	Not likely

By applying the climate change scenario in **Table 8.6** as the climate inputs, the outputs of the HDM-4 simulation show that the current Indonesian maintenance standards were found adequate to deal with climate change (see **Figure 8.16** and **Figure 8.17**). However, an optimal level of accessibility may be achieved if gravel roads are upgraded to bituminous roads, mainly to anticipate worsening climate change scenarios, e.g. CC2 and CC3. Thus, the upgrading scenario could be the best option for adapting to climate change.

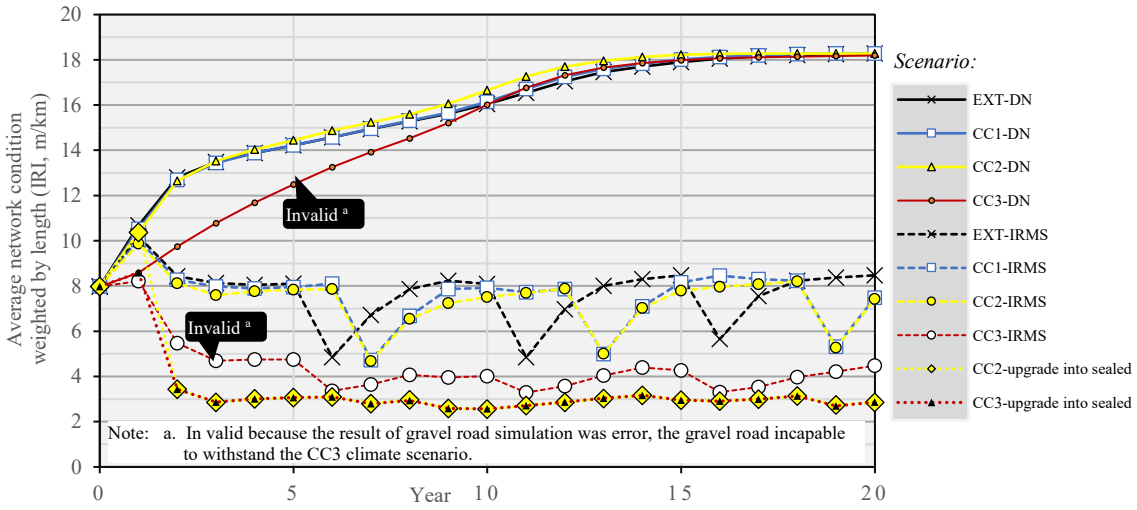


Figure 8.16 Climate scenario Vs Road network conditions

In terms of budget, the climate change scenarios increase the maintenance costs in the Kalsel province by up to 8.4% for the first five-years and 16.56% over twenty-years (see **Figure 8.18**). The cost for maintenance doubles when the CC2 and CC3 scenario occur, i.e. the climate zone shifted from tropical-humid become tropical-per-humid. This pattern indicates that the impact of climate change on accessibility is minimal when the parameter(s) remains in the same climatic zone but becomes significant when the zone shifts.

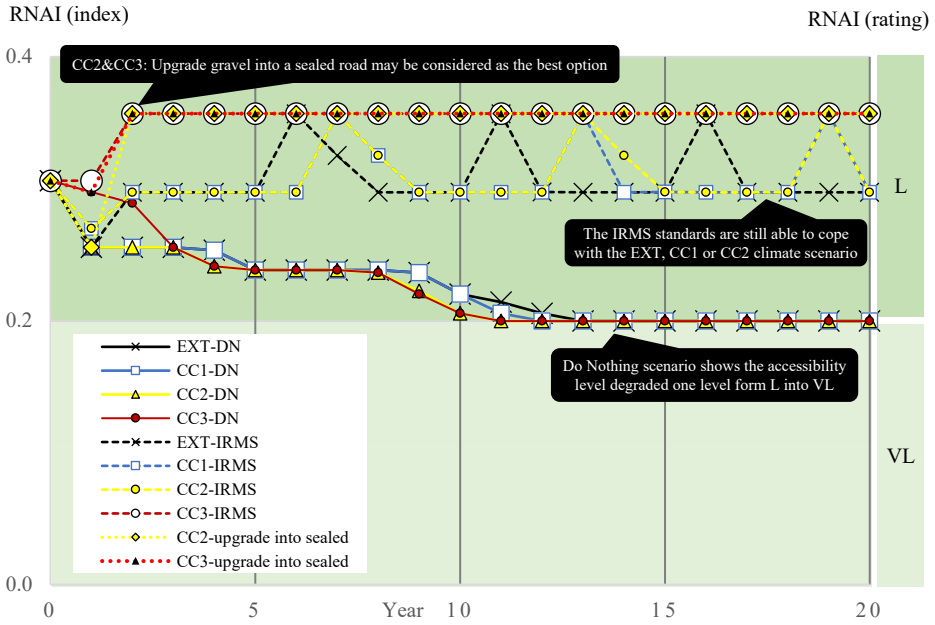
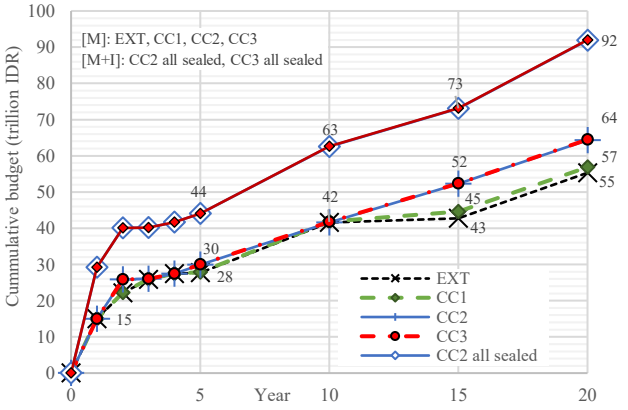
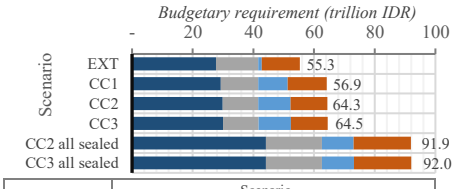


Figure 8.17 Climate scenarios Vs Accessibility



a. Cumulative budget requirement



Budgeting Period	Scenario					
	Ext	CC1	CC2	CC3	CC2 all sealed	CC3 all sealed
Y1-Y5	27.7	27.9	29.9	30.0	44.1	44.1
Y6-Y10	13.9	13.9	11.7	11.7	18.5	18.5
Y 11-Y16	1.1	2.7	10.6	10.6	10.5	10.5
Y15-Y20	12.6	12.3	12.1	12.1	18.8	18.9
Total 20 years	55.3	56.9	64.3	64.5	91.9	92.0

Where: EXT=existing climate; CC2=climate change scenario 2; Y1= year 1 (2015); CC2 all sealed: upgrade all gravel road into bituminous

b. Budget per 5-years period

Figure 8.18 Climate scenarios Vs Budgetary requirement

8.7 The Impact of Extreme Weather on Accessibility

Extreme weather events are difficult to predict, and the impacts vary depending on the characteristics of the EWEs (e.g. severity and duration) and the existing condition of road assets (see **Chapter 2**). Accordingly, as "the worst-case scenario", it is assumed that extreme weather events (EWEs) cause severe damage to roads and change them into poorly conditioned roads (IRI=12 for bituminous road and IRI=22 for gravel road). In this research, the scenario of extreme weather in Kalsel Province can be illustrated as follows. Extreme weather events (EWEs) occurred at the end of the year 2014 in the Kalsel province and damaged some roads. These events led road managers to repair the roads at the beginning of 2015 (first year of analysis period). Besides, fallen trees and damage from landslides also required emergency roadworks like land clearing or non-pavement-based maintenance which was estimated to have cost IDR 10 million (550 GBP) per km.

As discussed in **Chapter 7**, degradation due to extreme weather is generalised into four scenarios, i.e. lost bad sealed roads [3], lost bad unsealed roads [4], lost good sealed roads [5] or lost good unsealed roads [6]. Although the length of road degraded due to EWEs may vary, the degradation scenario is limited up to the total length of road networks in Kalsel Province, e.g. maximum length 737 km for unsteady-state gravel road condition (see **Table 8.7**). Accordingly, the EWEs impact may be assumed and represented by 5% road damage (626 km) to show an equal comparison for assessing the impact of the degradation scenarios on accessibility. For instance, scenario [5] which associated with damage in 626 km of a good-bituminous road may be represented by damage in 494 of 494 km RAT1R1 and 132 of 675 km RAT2R1 road category (see **Table 8.7**).

Table 8.7 Road degradation scenario due to extreme weather events

Road characteristics		Scenario [b]	Available road (km)	Road category which assumed to be damaged due to EWE
Road condition [a]	Pavement			
Un-steady state	Bituminous	[3] loss of bad sealed roads	3,371	RAT3R4, RAT2R4 [c]
	Gravel	[4] loss of bad unsealed roads	737	RGT6R4, RGT6R3, RGT5R4, RGT5R3 [c]
Steady-state	Bituminous	[5] loss of good sealed roads	4,457	RAT1R1, RAT2R1 [c]
	Gravel	[6] loss of good unsealed roads	4,012	RGT5R1 [c]

a. Steady-state = roads are in a good or fair condition; unsteady state= roads are in a poor or bad condition.
b. Based on the scenario in Chapter 7.3.
c. Using the partial length otherwise used the full length from the road representative category.

Based on the HDM-4 analysis, the results indicated that the current IRMS standards are capable of coping with extreme weather events scenarios (see **Figure 8.19** and **Figure 8.20**). However, as previously anticipated, it increases maintenance costs. The HDM-4 simulation pointed out that the worst impact of EWE scenarios on the budget is when they lead to damage on good sealed roads, i.e. scenario [5]. It was found that the impact of 5% road damage from EWEs in the Kalsel province increases the maintenance budget during the first 5-year period by 8.26% (**Figure 8.21**). The impact on poor road conditions was not found to be significant because roads are planned to be repaired following the roadworks threshold in the IRMS maintenance standards, regardless of the occurrence of EWEs.

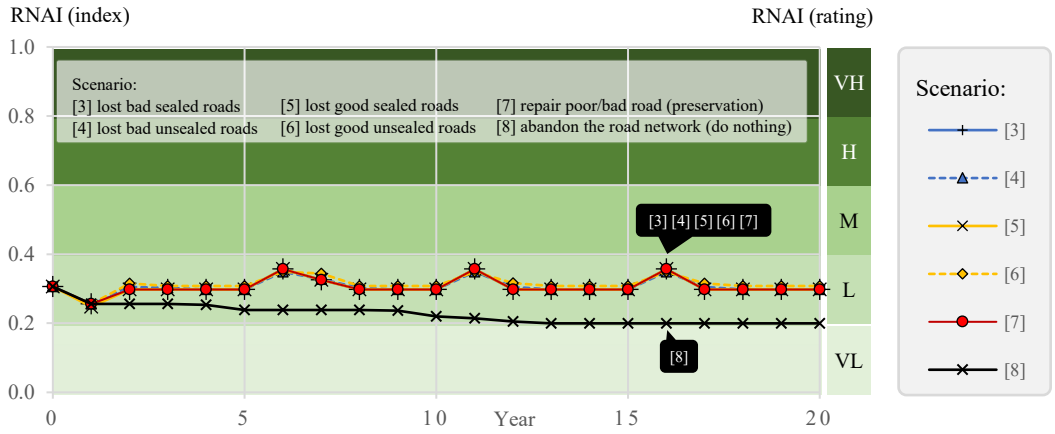


Figure 8.19 Road degradation scenario Vs accessibility index

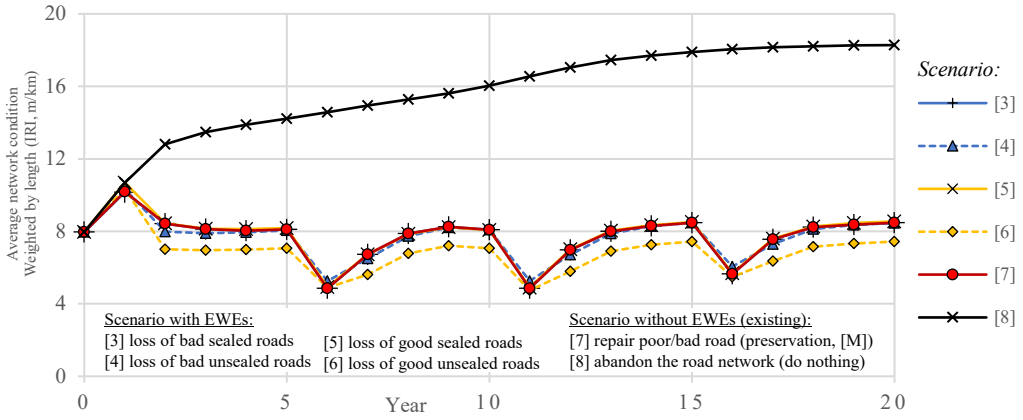
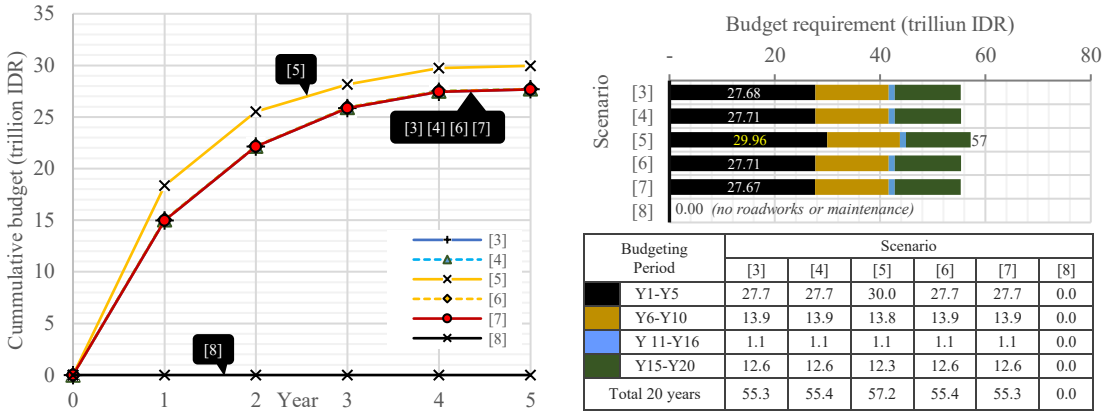


Figure 8.20 Road degradation scenario Vs road conditions



a. The first 5-year period

b. Twenty years of analysis (long term)

Budgeting Period	Scenario					
	[3]	[4]	[5]	[6]	[7]	[8]
Y1-Y5	27.7	27.7	30.0	27.7	27.7	0.0
Y6-Y10	13.9	13.9	13.8	13.9	13.9	0.0
Y 11-Y16	1.1	1.1	1.1	1.1	1.1	0.0
Y15-Y20	12.6	12.6	12.3	12.6	12.6	0.0
Total 20 years	55.3	55.4	57.2	55.4	55.3	0.0

Figure 8.21 The impact of road degradation scenarios on the maintenance budget

Based on the HDM-4 simulation as illustrated in **Figure 8.19**, when EWEs occur and road budgets are not increased, the accessibility value (index) is undoubtedly affected, but the level may remain the same, i.e. low level (L). However, as the worst-case impact scenario, the accessibility level in Kalsel province can be downgraded further from low (L) to the very low level (VL), following the do-nothing or do minimum scenario. This means that Kalsel province would be restricted in terms of services and opportunities. Road users would have limited route options, and the area may become isolated when EWEs occur and damage strategic road segment(s).

8.8 Adaptation Standards and Strategies

8.8.1 Adaptation Standards

Based on the analysis in **Chapter 8.4**, the HDM-4 simulation indicated that the current Indonesian maintenance standards (IRMS) are adequate to deal with climate change in Indonesia. However, there is a need to enhance the current IRMS gravel maintenance standards to optimise the condition of road networks. For avoiding the faster deterioration of gravel roads, routine maintenance such as grading should be performed more often. Grading, which is currently only performed twice a year, could be performed every 30 or 120 days. Based on the HDM-4 simulation, the results show that the grading frequency significantly impacts road conditions and makes the level of accessibility more consistent (see **Figure 8.22** and **Figure 8.23**). Also, since changes in the precipitation parameter give the most significant impact on road conditions, routine roadworks such as drainage maintenance and vegetation control should be considered to pre-empt trees falling in extreme weather, e.g. heavy rainfall, and strong wind.

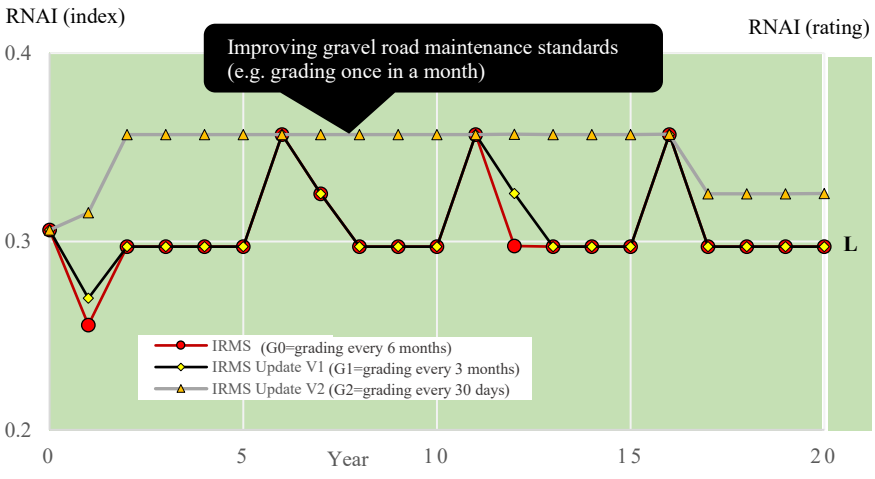
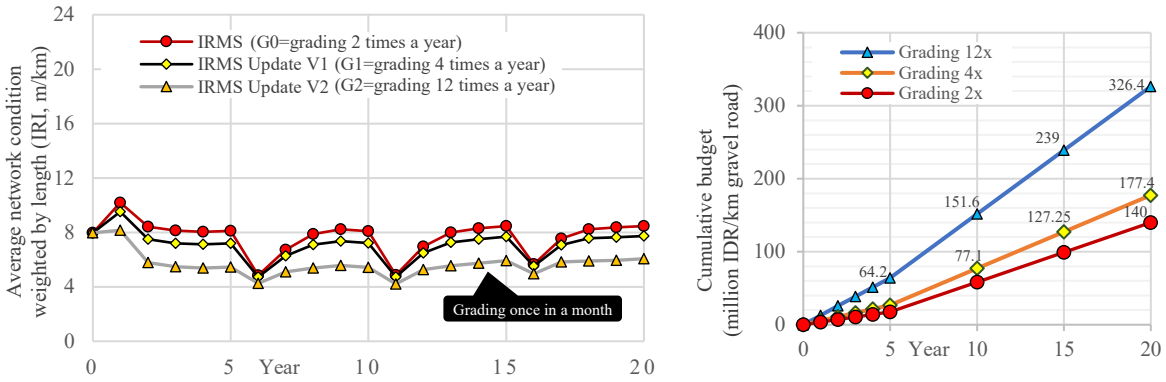


Figure 8.22 The impact of updating gravel road maintenance standards on accessibility (unconstrained budget)



a. Road conditions b. Budgetary requirement

Figure 8.23 The impact of updating gravel road maintenance standards on road conditions and budgetary requirement (unconstrained budget)

8.8.2 Accessibility Management Strategies

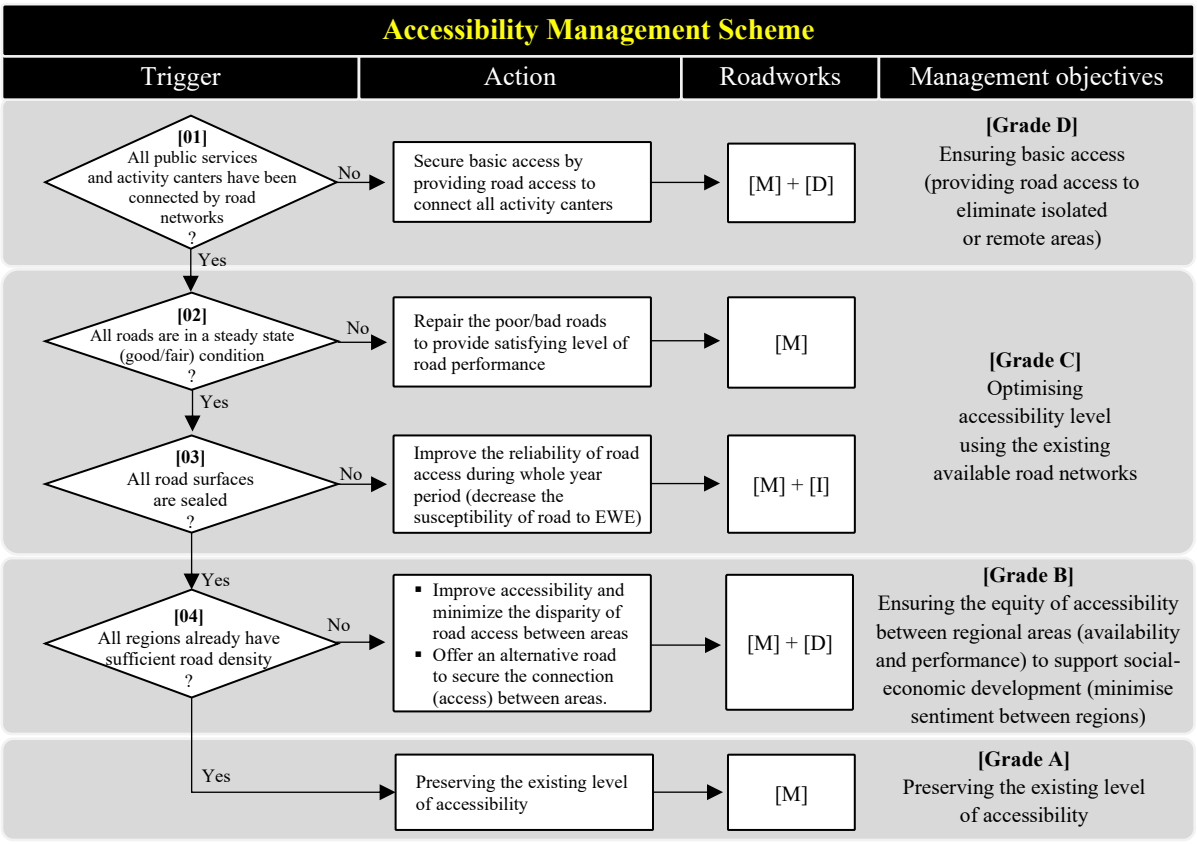
Currently, there is no robust method to resolve uncertainty. However, learning from historical climate patterns, climate projection models may still be the most appropriate approach to manage asset conditions under climate change exposures. Decision-makers need to be informed about how uncertainties in future climate parameters affect the road performance and budget. Therefore, in road asset management, the lifecycle-cost analysis needs to consider climate projection scenarios and its potential impacts on road pavements. Meanwhile, the high uncertainty impacts of climate change like natural hazards and disasters cannot be directly addressed because of limitations in the HDM-4 software and climate model. However, since natural hazards generally happen in a small area, special preventive roadwork can be introduced to protect road assets. Areas susceptible to climate exposure are identified on a hazard map issued by the local government. In the worst-case scenario, the road infrastructure is automatically (instant) damaged and requires emergency roadworks following natural hazards in vulnerable areas identified on the natural hazard map. A typical example of a disaster risk (natural hazard) map for Indonesia is shown in **Appendix B**.

In general, accessibility management strategies vary depending on the situation and condition. There is no universally applicable solution for every situation. However, some options are

useful for responding to specific events, meeting a goal(s), and adhering to a budget, amongst other considerations. Road asset management is a broad field in which the main emphasis is on providing a service and optimising road conditions through engineering and economic (cost-effectiveness) measures. It means, along with the technical aspects, management strategy should analyse the long-term impact on cost and benefit. Although, the global economic perspective in the transportation sector has changed over the past century, i.e. from miles of highway (industrial era) to information technology applications for travel time reduction (post-industrial). They both share the same perspective, i.e. road infrastructure should be built properly in advance to provide basic access for residents (Stimson et al., 2006). The availability of road infrastructure not only opens an isolated region(s) but also acts as a precondition to trigger further development of other public infrastructure like electricity, telecommunication, and public services (Banister and Berechman, 2001). Once the connection is available, the quality and reliability of access can be considered following the proposed general scheme of accessibility management, as shown in **Figure 8.24**.

Overall, climate change and extreme weather adaptation strategies encourage road managers to provide robust network connections with good quality roads. However, a strategy to enhance national accessibility level should also be considered to improve accessibility and its distribution across the nation. When the budget is limited, the option to optimise accessibility using existing road assets (without building a new road(s)) is highly recommended. As illustrated in **Figure 8.25**, the accessibility level in Indonesia could be enhanced by giving priority to (1) upgrading the gravel roads in regions with low (L) or medium (M) levels of accessibility; (2) double the road assets (build new roads) to increase component N, C and P simultaneously in regions with very low (VL) accessibility; and (3) preserve the current

accessibility in regions with a high (H) or very high (VH) level by implementing periodic maintenance following the IRMS standards.



Where: M= Maintenance: routine and periodic; I = Improvement: upgrade unsealed road(s) into a paved road(s); D = Development: build new road(s).

Figure 8.24 Proposed strategies to managed accessibility

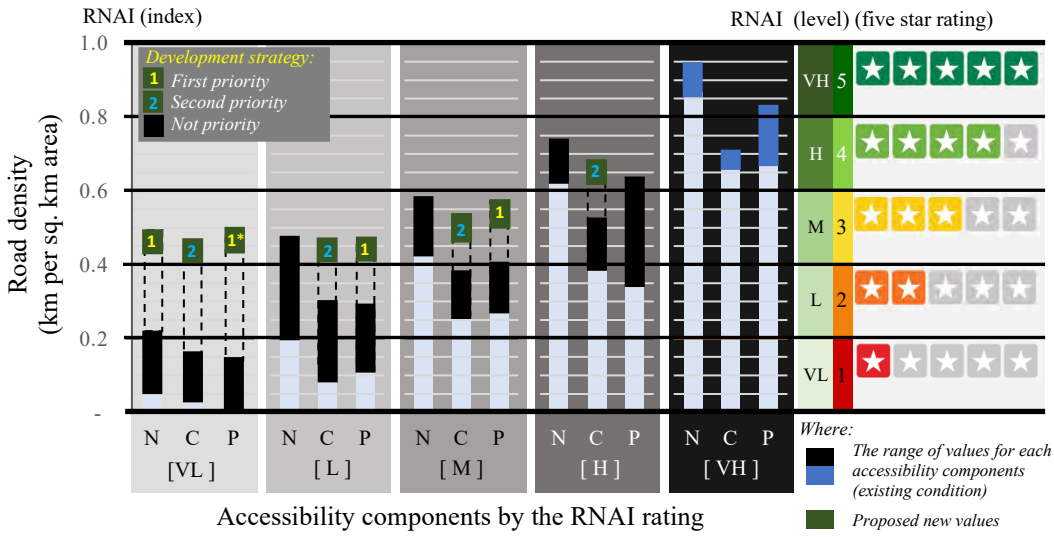


Figure 8.25 General scheme to enhance accessibility level in Indonesia

For a local context (e.g. province level), the improvement strategy may vary depending on the current condition of road assets and their distribution. Thus, the improvement strategy should be assessed case by case following the flowchart of accessibility management scheme, as shown in **Figure 8.24**. For general cases in Indonesia, road managers could improve the accessibility level based on the priority order, as shown in **Figure 8.25**. For example, in a region with a very low level of accessibility (VL), as identified by a yellow number one (1*) sign in the component P, the first priority could be to improve component P which could improve component C simultaneously, e.g. upgrading a gravel road in a bad condition into asphalt road. Afterwards, as a yellow number one sign is shown in component N, the second priority could be to improve component N. This option is endorsed because it increases component P immediately, e.g. building new asphalt road segment(s). The last priority is improving component C (shown as a blue number two sign). In general, preserving road condition (the value of component C) is a mandatory option in road asset preservation schemes. For a development scheme, it is more effective and efficient to increase component C by improving other components simultaneously, i.e. N and P (see the relationship between accessibility components in **Chapter 9.2.3**). Nevertheless, as Figure 8.25 only provides a general scheme of accessibility improvement in Indonesia, these priority scenarios and strategies still need to be assessed and simulated using HDM-4 to ensure the cost-effectiveness.

CHAPTER 9

DISCUSSION

9.1 Introduction

This chapter presents a discussion about the newly developed accessibility model, i.e. the road networks accessibility index (RNAI), concerning the theoretical concepts, modelling approach, measurement technique, and the contributing factors included in the model. The application of the proposed concept to manage accessibility levels in Indonesia under climate change and extreme weather conditions are also elaborated. This chapter is presented in five sections. Initially, it discusses the development approach and originality of the RNAI model. The transferability of the model for other countries and how good the RNAI model compares to the World Bank model is reviewed. Afterwards, the next section elaborated the use of RNAI model to manage accessibility under climate change and extreme weather scenarios using the road asset management tool HDM-4. The last section describes the further application and impacts of accessibility management in Indonesia.

9.2 The Road Network Accessibility Model (RNAI)

9.2.1 General Concept and Development of the RNAI

Transportation infrastructure plays a crucial role and is the backbone for supporting regional development (Nigohosyan and Vutsova, 2018). Although regional development may be multi-dimension and have many perspectives (Pike et al., 2010), as elaborated in **Chapter 3**, the previous accessibility models focused more on the land use aspects than transportation infrastructure. To date, the only available road infrastructure-based accessibility index is the road density measurement developed by the World Bank. In application, this measurement may

be appropriate for developed countries where the roads are typically bituminous and always well maintained. This top condition of road assets offers optimal road performance and keeps maintenance cost at a minimum or in a steady-state condition. Accordingly, roads will always be open (in-service) and give their best performance for the daily traffic. Still, this ideal condition of road asset cannot be applied in developing countries because of the minimal budget for managing road assets. Despite some developing countries claiming that they have an excellent accessibility level because they have built numerous lengths of road (high road density). The real perceived accessibility level remains low because the road conditions are generally poor, or the road network dominated by gravel roads which are not accessible during heavy rain. Thus, measuring accessibility using road density may still be appropriate in developed countries, but it will cause biased measurements and interpretations when it is implemented in developing countries.

To this end, the new RNAI model enhanced the existing accessibility measurement from the World Bank, i.e. road density, by introducing road condition (C) and type of road pavement (P) as additional features to address the different characteristic between developing and developed countries in road assets. The RNAI model satisfies not only the theoretical aspects of accessibility but also the practical aspects of developing countries. The model can cover the real aspect of accessibility by considering the concept of equity and the economic life of road infrastructures **(see Chapter 9.2.2)**.

By using Indonesia as a case study, the RNAI model has been successfully linked the concept of accessibility with the existing road asset management (RAM) appraisal tool, e.g. HDM-4, and used it to deal with climate change and extreme weather events scenarios. Some analytical assessments to show the robustness of the RNAI model are elaborated in **Chapter 7** and

Chapter 8, e.g. through sensitivity and scenario analysis along with the economic appraisal on lifecycle costing.

Intended to be implemented in developing countries, the RNAI was developed using a simple linear model which is easy to calculate and interpret. In principle, some experts may be doubting the concept and application from the new RNAI model. They may argue that a simple model may not directly include many factors, e.g. travel time, traffic and land use. However, a simple model is not an inadequate model. A simple model may even be better because it is transparent and has a "smart" goal, i.e. the goal is specific, measurable, attainable, relevant and time bound. Thus, the developed RNAI model is:

1. *Transparent*: the RNAI has precise, unambiguous components and indicators that are familiar to stakeholders for managing the accessibility level. In Indonesia, the required data for calculating the RNAI are also available for public (free download or upon by formal request). By knowing how the index behaves and the required data are also available, it improves the practical aspect of the RNAI model to manage accessibility level and increases public awareness for ensuring the road asset is appropriately managed. This transparency becomes a vital aspect that may be used to minimise/anticipate political interference or corruption scheme that may arise, especially related to budget allocation.
2. *Specific*: the RNAI model gives a clear definition along with explicit goals that want to be achieved. The model tries to improve accessibility using road asset management perspectives, i.e. focus on road infrastructure features and their condition.
3. *Measurable*: the formula to measure the accessibility model (RNAI) is very clear and straightforward. The index is also easy to interpret and associated with popular indicators such as the star-rating system.

4. *Attainable/achievable*: the target of accessibility should be set by considering the current level of accessibility. The initial objective may be set to provide basic access and minimise the disparity of the accessibility level by optimising the existing road networks (see **Chapter 8**). When an extra budget is available, the accessibility can be level up further by building a new road(s).
5. *Relevant/realistic*: the available options and strategies to manage accessibility are in line with the road manager's responsibility as the primary user of this model. Although the accessibility model can be used as a stand-alone tool, in this research, it is linked with the HDM-4, the standard decision support tool in road asset management. Thus, accessibility management can be integrated with the existing road asset management regime.
6. *Time-bound*: The accessibility model has time-constrains that request roads should always be open or in-service (accessible) throughout the year. Also, the scenario and target of accessibility level may be specifically bounded with a time constraint. For instance, the accessibility may be gradually upgraded but should always meet the minimum target or standard within five years (short term) management period.

9.2.2 Contributing Factors Included in the Accessibility Models

9.2.2.1 The concept of equity

The new road networks accessibility index (RNAI) uses the same unit of measurement, i.e. road density. However, it includes the maximum national value from each accessibility components as an accessibility target to ensure the equity in the distribution of accessibility level is satisfied. This technical approach is suitable when no national/international standard is available. However, once it is available, the target value may be substituted by that standard.

In Indonesia, quantifying the RNAI components in the form of "road density" gives a better judgment in the context fairness of treatment between regions than in the form of existing

measurement, e.g. “percentage” of road length in a steady-state (good/fair) condition. The same percentage of roads in good condition can result in a different length of the road when the total length of road networks is different. In reality, this illustrates the unfair treatment between big and small cities in road asset development. For example, two regions (A and B) have the same land area, i.e. 450 km square. In region-A which has 1,000 km of roads, 70% means the region has 700 km of good/fair road condition, but in region-B which has 500 km of roads, 70% means that the region only has half of it (350 km of good/fair road condition). Accordingly, region-B has a lower accessibility level, yet it was considered equal.

In contrast, the use of road density (e.g. 0.7 km per sq.km of good/fair road condition) will provide equally 315 km of roads in a good/fair road condition for each region. This example illustrates that quantifying road performance in the form of “road density” offers a more consistent measurement than quantifying it in the form of a “percentage” and may ensure fairer investment in road assets within a country. Accordingly, the use of road density as the base form of measurement in the RNAI model satisfies the concept of equity.

9.2.2.2 Component to measure accessibility

In the technical aspect of accessibility, road infrastructure does not only need to be available but also be in a good/fair condition to provide optimal road performance. In this case, the notion to explicitly use road infrastructure features as the accessibility indicator ensures that the model of accessibility may be practically integrated with road asset management tools like HDM-4. Also, the RNAI model points out that, due to the recent issue of climate change, the road network is required to be always in service in all weather conditions. The lifecycle cost analysis results in **Chapter 8** highlighted that the reliability of access and road performance dramatically increase when gravel roads are upgraded into bituminous roads. Furthermore, sealed pavement

(e.g. asphalt road) has been tested and verified to be more resistant than gravel roads at adapting to climate change and extreme weather events (see **Chapter 4**).

9.2.3 Relationship Between Accessibility Components

In road asset management, although it may not be significant, changing one of the accessibility components may have an indirect impact on the other components. For instance, in road work maintenance standards, improving accessibility through the length of the road network (N) by building a new road(s) can indirectly improve the length of roads in a steady-state (good and fair) conditions (C) and may also increase the length of sealed roads (P) at the same time depending on the pavement type of the new road(s) (see **Figure 9.1**). This relationship should be considered when proposing the best roadwork options for managing road network accessibility. This relationship may become a weakness of the RNAI model. However, the model is still valid for a "short" period, e.g. one year or a point in time. Then the dependencies are dealt with by HDM-4, i.e. using lifecycle cost analysis.

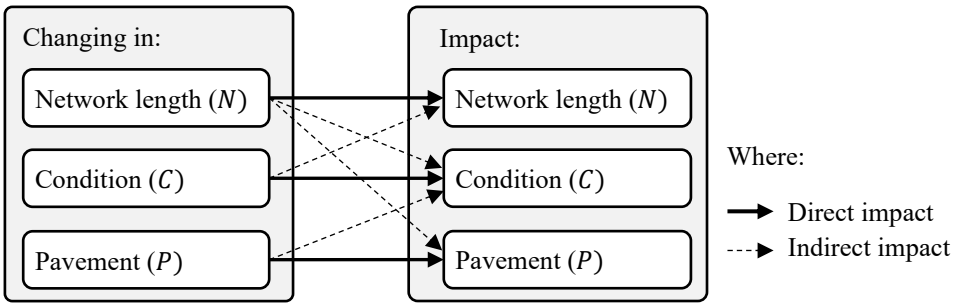


Figure 9.1 Relationship between the RNAI components

9.2.4 Transferability

The RNAI model was developed using Indonesia as a case study for representing developing countries. However, the RNAI model may be transferred and adapted, following local conditions and characteristics in different countries or areas. Furthermore, the RNAI index can

compare accessibility relative to international benchmarks, e.g. OECD Asia-Oceania countries, using an accessibility calibration factor (see **Chapter 6.4**).

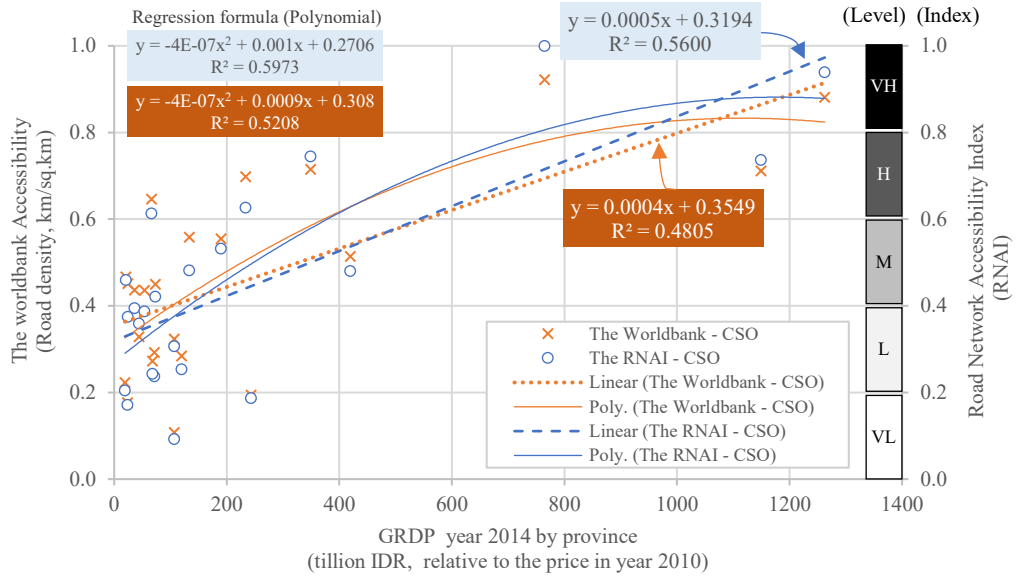
In general, comparing the accessibility level between countries may be challenging because of the availability of data, and the lack of consensus about standard levels of accessibility. Another attribute in the RNAI component that may be adjusted is the term of good and fair road condition. This term follows subjective preferences and each country has different standards of road performance. For instance, in a developed country such as the United Kingdom, roughness with IRI=7.8 m/km may be considered poor, but in developing countries, it is categorised as a fair condition. Besides, categorising road condition is not only based on roughness but also visual assessments of the pavement condition index (PCI). In the RNAI model, the categorisation issue has been anticipated by the explicitly stated "good and fair" road condition, which gives more flexibility for transfer application in any country. As long as the country has the same standards across its traffic or road classes, it is not a problem. If they differ, the accessibility can be applied relative to an International Benchmark by multiplying the value with an accessibility calibration factor.

Another common issue due to the existing road standards is the variation in the categorisation of road condition between sealed and unsealed road. This issue conceptually has been anticipated by exclusively calculating the density of "sealed" road (P) as the RNAI component along with the density of "good and fair" road condition (C). The minimal interference to the existing standards supports the integration of the RNAI model with the existing road asset management (RAM). As a result, the smooth transfer feature in the RNAI model may increase the acceptance of model applications for managing accessibility levels in any country.

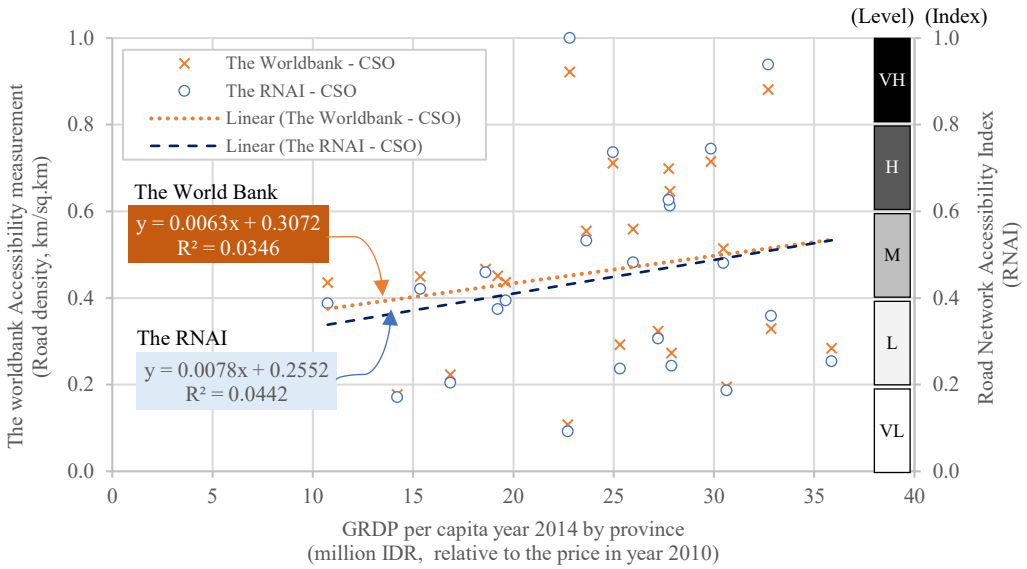
9.3 Comparison of the RNAI Model with the World Bank Model

There is a continuing debate regarding the role of transport infrastructure and changes in accessibility on regional economic development. Accessibility is essential to promote social and economic development (Talpur et al., 2016). Nevertheless, it is often debated because it is difficult to evaluate the changes in accessibility to regional economic development (Vickerman et al., 1999). Gross domestic product (GDP) is a popular measure of a country's economic productivity. When the unit of analysis is changed from national to regional (provincial) level, the term GDP is often changed to gross regional domestic product (GRDP) to clarify the level of analysis. Similar to GDP, GRDP often used by economists for indicating the economic productivity of region, while GRDP per capita is often used for measuring the wealth and prosperity of a region.

In general, the regression results in **Figure 9.2a** confirmed that the new RNAI model provides a slightly better explanation to demonstrate the relationship between accessibility and economic productivity (GRDP) than the World Bank model, i.e. road density (the RNAI with R^2= 0.56 and the World Bank model with R^2=0.48). However, as reflected in the coefficient of determination value (R^2), there is a weak relationship between accessibility and GRDP per capita, i.e. 4,42% for the RNAI model and 3.46% for the World Bank model (see **Figure 9.2b**). This weak correlation or relationship indicates that regional accessibility development has little impact on the economic welfare and prosperity of a region. Therefore, it is difficult to predict or explain the variability in regional welfare using accessibility as a determinant indicator. Thus, along with the road infrastructure development, the Indonesian government still need to consider the development of other sectors to support regional economic development, e.g. education, public services, and telecommunication infrastructure.



a) Accessibility Vs Gross Regional Domestic Product (GRDP)



b) Accessibility Vs Gross Regional Domestic Product (GRDP) per capita

Figure 9.2 Accessibility Vs Economic Development Indicator in Indonesia by province

In terms of economic prosperity, **Figure 9.2b** shows an interesting pattern of data distribution, i.e. there is a wide scatter of data after GDRP per capita reached 20 million IDR. When the graph was separated following the regression discontinuity approach, the correlation value for the RNAI increased substantially (double) from 3.46% to 5.31% and 9.17% (see **Figure 9.3**). It is indicated that the separated regression offers a better explanation for the relationship. The

data shows that on the left side of GRDP per capita 20 are the provinces of Nusa Tenggara Timur, Maluku, Nusa Tenggara Barat, Maluku Utara, Gorontalo, Sulawesi Barat. These are provinces where the population has a low level of education and mostly work in agriculture and fishing. Meanwhile, the population of provinces located on the right side are more well educated and work in more varied sectors, including trading, services, and manufacturing (KPPN and BPS-Statistics, 2015). This finding indicates that regional prosperity is not only influenced by accessibility level but also by other regional demographics like occupation and education level.

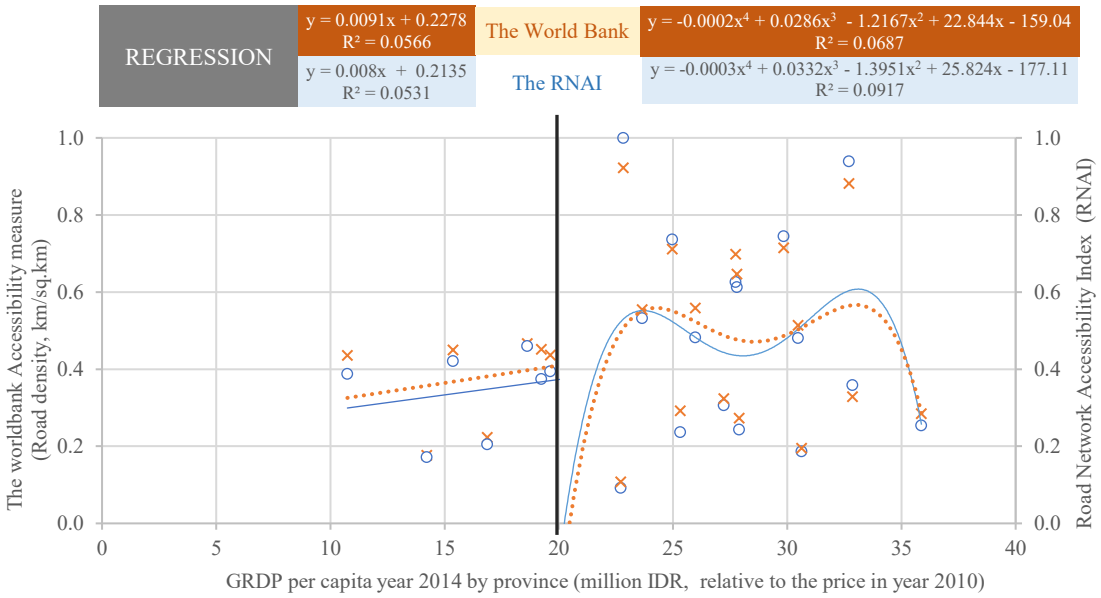


Figure 9.3 Accessibility Vs Economic welfare and prosperity

In terms of social development, the regression analysis proves that there are a definite pattern and a positive relationship between accessibility and population density (see **Figure 9.4).** **Figure 9.4** illustrated that the higher population density requests a higher level of accessibility. Correspondingly, this relationship shows that a higher accessibility level attracts more people for social activities and who move there for a better standard of living. However, it was noticed that the relationship is not linear but parabola. Accessibility value increases as the population

density increases, but at a certain point it peaks and then decreases. This pattern satisfies “the law of diminishing marginal returns” which states that at a certain point adding further input in production results in relatively smaller increases in output. The incremental effect of additional inputs may become zero and then negative. It means that the development of accessibility through road infrastructure at some point may peak and cannot solely improve the regional development. After reaching the peak level (e.g. 800 population per sq. km), the main issue of accessibility development is in the movement (mobility) of goods and people, which may be addressed by increasing road capacity, public transport, and traffic management. In infrastructure, the focus is not for adding to the length of road but to increase the capacity of current road segment(s) by adding an extra lane or widening the road segment(s).

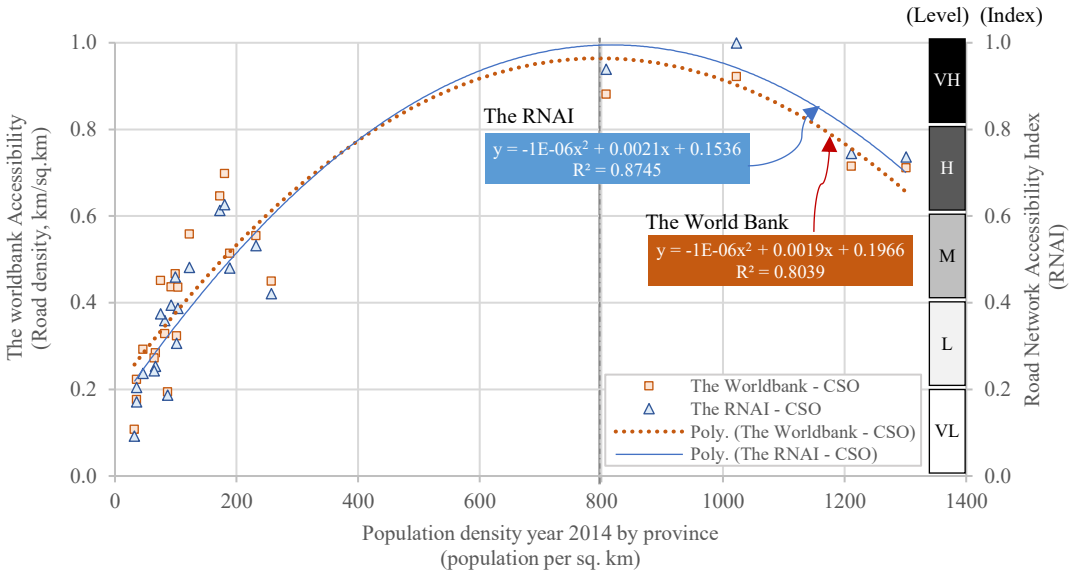


Figure 9.4 Accessibility Vs Population density by the province in Indonesia

Concerning the budget, it is noticed that increasing population density increases traffic (higher traffic load) which results in a substantial increase in road maintenance costs. Often, the local government may not provide additional budget because the revenue gained from road tax is not worth the additional cost required to maintain the quality of the road. As a result, the road

condition worsens faster, and regional accessibility decreases. In practice, this justification pointed out that management of accessibility needs to be synchronised with management in other sectors, e.g. traffic demand management and land use management, which are not directly included yet in the RNAI model. Once the disparity of the accessibility level between regions is minimised, the level of attractiveness of each region will be more similar. Also, the current migration trend which sees people seeking better jobs and opportunities in areas with high accessibility like Jakarta will be reversed and the population more equally distributed across the country (see further discussion in **Chapter 9.5**).

Concerning the comparison between the two-accessibility model, the regression analysis shows that the RNAI model gives a better explanation to show the relationship between accessibility with regional economic development than the previous World Bank model, as represented by the higher value of regression coefficient. **Figure 9.2, Figure 9.3** and **Figure 9.4** may explain the reason for the continuing debate that has risen between stakeholders about investment in road infrastructure. The figures show that investment in road infrastructures for improving accessibility could directly impact economic productivity and social development but not regional wealth and prosperity, e.g. GDRP per capita. The impact on regional prosperity may be felt in the long term though from increased economic productivity. Road assets are believed to be a prerequisite to enhance regional development. Without sufficient road infrastructure (quantity and quality), regional development is hindered, both socially and economically.

9.4 Accessibility Management to Cope with Climate Change and Extreme Weather

9.4.1 Method for Representing Climate Change and Extreme Weather Scenario in HDM-4

Based on the HDM-4 simulation as presented in **Chapter 4** and **Chapter 8**, the results indicate that existing asset management systems could efficiently deal with the long-term impacts of climate change. However, such systems are insufficient to deal with extreme weather conditions

caused by climate change. The input of the climate parameter in the HDM-4 may only be adjusted to represent a static climate which remains the same during the analysis period. A sudden change in the climate parameter over a short-term period, e.g. in an hour(s) or day(s), cannot be directly addressed using HDM-4 simulation. The option to input the extreme weather parameters in the HDM-4 gives an over design road pavement which results in high maintenance costs for the road asset during its lifecycle.

Although the static climate parameter has been adjusted and tested to mimic the dynamical pattern of climate change by gradually increasing the climate parameter every five-years, the HDM-4 outcome leads to biased result (See **Chapter 4**). The bias is because it always asks for maximum investment in the early years of analysis so that maintenance costs for the following years are kept to a minimum. Thus, long-term analysis cannot be associated with short-term analysis even though it has been simulated in series order as presented in **Chapter 4.5**. The best approach to simulate climate change in HDM-4 is to directly set the climate input based on the climate scenario in the final year of the simulation period, e.g. the next ten or twenty years. Because increases in the climate' parameter are not significant, and making the change can take decades, this approach is theoretically accepted by assuming it as the worst-case scenario.

9.4.2 Climate Change and Extreme Weather Adaptation in Accessibility Management

Climate effects are subject to uncertainty. In general, it is difficult to visualise and simulate how an extreme weather event (e.g. landslides, floods, heatwaves) will affect the overall road condition and accessibility. Managing road assets to meet the need for uncertainty in future climate risks such as extreme weather events may result in the over design and maintenance of road structures. Although the uncertainty in climate projections can be managed using climate models (ADB, 2015), the strategies for extreme weather adaptation offers many solutions, depending on the climate scenario and constraints involved.

The second aspect is the uncertainty about the time and location where the extreme weather will occur. Theoretically, this uncertainty in the time-space may be addressed by considering the historical pattern of extreme weather events (EWEs), including the topography of the region and return period of EWEs. In Indonesia, the Indonesian National Board for Disaster Management (BNPB) has issued a vulnerability map of disaster, and the Indonesian Non-Departmental Government Agency for Meteorology, Climatology, and Geophysics (BMKG) also issued a climate projection and weather forecast periodically. However, this type of information only gives a prediction as a likelihood (risk function) instead of a definite/specific weather event.

In general, the HDM-4 analysis in **Chapter 8** has shown that climate change does not substantially impact the accessibility level in Indonesia. The change in the climate parameter for the future twenty years analysis may be covered by the exiting IRMS maintenance standards with an insignificant difference in budget requirement (see **Chapter 8.5**). However, the cost is entirely different when dealing with the uncertainty of extreme weather events. It is almost impossible to fight the forces of nature like storms and heatwaves. The historical data in **Chapter 4** shows that extreme weather events always damage road infrastructure, and road access is lost. Although the loss of access is temporary (hours, days or month), it costs extra because road managers need to perform an immediate emergency response.

The most appropriate countermeasure for extreme weather is adapting or avoiding the risk (see **Chapter 3.5**). When the risk is high, in terms of accessibility management, the RNAI model advised to build new roads as alternative routes when the vulnerable road segments are deteriorated or destroyed from EWEs. In this case, the road network infrastructure should be viewed as a system, not as an individual road segment(s). Meanwhile, when the risk is low, the road managers may ignore the EWEs' treat with a note that road conditions must be kept

maintained and managed to provide an optimal accessibility level under budget constraints. However, if that vulnerable road segment is a vital asset, e.g. part of a historical asset, an option to strengthen and protect the existing infrastructure may be used, but with a drawback of a higher budget for the protection scheme and maintenance.

In general, regions with a higher level of accessibility typically have higher road density (see **Chapter 7.2.1**). This pattern indicated that the higher the accessibility level of the region, the more robust of the region to withstand climate change and extreme weather conditions. They have more roads which act as alternative roads to provide more reliable road connections (access) throughout a network. Road segment(s) may be destroyed, but the road network as a system always provides access to road users for the whole year.

9.4.3 General Scheme for Accessibility Management

Based on the RNAI formula, the RNAI has three components, and each component makes an almost equal contribution to the model, i.e. 33% (see **Chapter 7.2**). However, because the condition of road pavement is not in static but deteriorates over time, based on the lifecycle of analysis (see **Chapter 8.4**), the increase in road length (N) may have a more durable impact on accessibility. For instance, building a newly sealed road(s) may increase the three components of accessibility at a time, and sealed road networks are more resistant to climate and traffic load than gravel roads (see **Chapter 9.2.3**). Thus, the impact of accessibility improvement will last longer.

In contrast, repairing a bad road into a good road only has a temporary impact on the level of accessibility because the road will deteriorate again over time regardless of whether it is open or closed to traffic. For upgrading strategies, i.e. upgrading gravel roads into bituminous roads, this option may have an intermediate impact compared to the two previous options. It is because the upgrading scenario may increase accessibility by improving the overall road conditions and

holding the road networks in a steady-state (good or fair) condition longer than gravel roads. However, over time, the newly upgraded road(s) still need periodic maintenance, to ensure that the roads are always in the best condition possible.

In terms of long term strategic analysis, based on studies in an accessibility benefit measurement, Junoasmono (2004) and Miller (1999) also demonstrated that improving accessibility from bad to good condition is more beneficial than improving accessibility from good to excellent condition. It indicated that ensuring the availability and equity of road infrastructure as well as its conditions (pro-active, road management to generate more traffic) is more effective for supporting regional development than improving a particular part of road which has higher traffic volume (responsive, road management follow the demand of traffic). Thus, the proposed strategy in **Chapter 8.8.2** to set the availability of road connections as the top priority in managing accessibility will free up regions from isolation and increase the social-economic activity and income level. Afterwards, the condition and reliability of access can be considered once all public services or activities are connected by at least one road to the region's road networks.

9.5 The Use and Impact of Accessibility Management in Indonesia

9.5.1 Accessibility as a Tool to Strengthen the National Integrity and Regional Development

A road network is a vital asset to connect services across a country (Sreelekha et al., 2016). Due to different characteristics of regions, the number of road assets between regions varies depending on the financial budget and the demand for transportation. Since the colonial era, the development pattern of road asset in Indonesia has been typically good but only concentrated on Java island where the capital city Jakarta is located (van Leeuwen and Földvári, 2016). The further the distance of the region from the capital city, the less development was made. This situation makes Java become a great showcase of Indonesia with complete facilities, e.g. toll

roads, railways, international airports, seaports, high-rise buildings, and advanced medical and educational facilities. In terms of the accessibility index, Jakarta surprisingly has ten times more than the average level of accessibility in Indonesia (see **Chapter 6.2**). In the national context, this condition makes other regions (outside Java island) seem left behind, particularly in the transportation sector, as well as the essential infrastructure for triggering development, e.g. electricity, communication, and water (Soseco, 2016). Also, a high level of accessibility in Java island means it is a magnet for people seeking better opportunities, either for a better job, education or standard of living. Consequently, almost all regions outside Java island are losing workers who are at a productive age. These workers are a valuable human resource, who are critical for social-economic development. The migration of workers was later identified as one of the main reasons for the higher multi-sectoral disparity between regions (Suryahadi et al., 2009).

The low and unbalanced accessibility development may trigger negative impact such as adverse sentiment between regions which can result in independence referendums, e.g. Timor Timur (Timor Leste) in 1999 (Cummins, 2010). Learning from that experience, to accommodate the petition for accelerating regional development and minimising the disparity between regions, Indonesia government facilitated this goal with the "pemekeran wilayah" scheme or regional proliferation, i.e. splitting a province/district into some provinces/districts. According to the data from the Indonesian Ministry of Home Affairs official (see **Table 9.1**), it can be confirmed that, since 1999, there have been 223 new proliferation areas in Indonesia, i.e. eight provinces, 181 districts and 34 municipalities (urban district). The purpose of proliferation is to reduce the coverage area for management so that the development can be concentrated. Also, as one of the tangible impacts, the new areas get an extra budget to speed up their regional development, e.g. extra road maintenance and development budget for accessibility management.

Table 9.1 Regional proliferation in Indonesia
(after Indonesian Ministry of Home Affairs, 2019)

Level of government or regional area	Regional proliferation (new area)		Total regional area (2019)
	(1999-2004)	(2005-2014)	
Province	7	1	34
District/Regency	115	66	415
Municipality	26	8	93
Total	223		542

a. For the year 2015-2019 (now), there is no new area due to moratorium policy for regional proliferation

In 2019 the Indonesian government under the presidency of Joko Widodo announced a plan to move the capital from Jakarta on Java island which has an excellent (VH) level of accessibility, to Kutai Kartanegara on Kalimantan island, which has a very limited (VL) level of accessibility (see **Figure 9.5**). One of the main reasons, for the proposal, is accessibility and its distribution to support regional development along with avoiding the risk of extreme weather events due to climate change (Bappenas, 2019). These past experiences from Indonesia indicate that the lack of accessibility and disparity generate multiplier effects, including triggering sensitive issues that threaten national unity. Therefore, the accessibility level should be managed equitably.

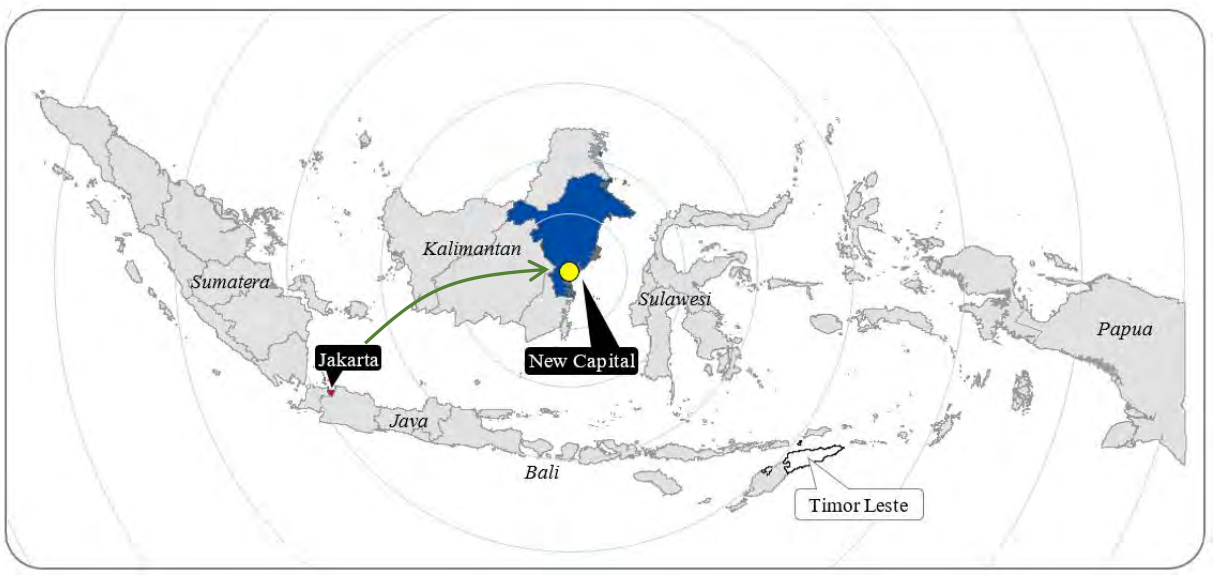


Figure 9.5 Indonesia moving the capital to ensure equity distribution in development and avoid extreme climate events risk

9.5.2 The Use of the RNAI Model to Anticipate Latent Impact of Accessibility Development

In developing countries, it is always easy to build a new road(s) because it is popular and has a bigger budget than road preservation. This option also becomes an attractive project for politicians in parliament, especially near the campaign period once in five years, to get public sympathy. Although it may be categorised as a harmful political interference, road managers should be smart (adaptive) and use this situation as an excellent opportunity for proposing the accessibility improvement scheme, i.e. building new roads to speed up the regional social-economic development. Also, it should be noticed that all scenarios have side effects. In developing countries, it becomes a 'latent' problem because the side effects are often neglected or forgotten by politicians and road managers, i.e. the works are not finished yet when the roads have been built because the new roads also need to be managed.

Consequently, it should be anticipated that the total preservation cost increases because the total length of road assets that need to be managed increases due to the new roads. The RNAI model which is simple, transparent and easy to interpret, it could be a big opportunity for road managers/authorities to educate stakeholders, including politicians and road users, that roads not only need to be built and maintained but also managed. Also, to maintain accessibility, the road network must be viewed like an asset of which the value depreciates over time. Once stakeholders understand how the accessibility index (RNAI) behaves and is linked with road asset management, it will be more comfortable and faster for road managers to get budget approval for improving accessibility. Either for routine/periodic maintenance, upgrading gravel roads, or even building new roads.

CHAPTER 10

CONCLUSIONS AND FURTHER WORK

10.1 Conclusions

This research has developed a new methodology and associated models for assessing the level of accessibility in a region. The developed accessibility model (RNAI) was successfully tested using Indonesia as a case study. The RNAI model has successfully proven that it may be linked to an economic appraisal like the HDM-4, the standard decision support tool in road asset management. The model satisfies not only the theoretical aspect of accessibility but also the practical aspect of economic appraisal in road asset management regime to deal with climate change and extreme weather conditions.

The general conclusions drawn from this research are as follows:

A. Development of the Accessibility Model

1. The use of the accessibility method was demonstrated in Indonesia and proved successful.
2. The inclusion of road conditions and pavement types as additional components of accessibility increases the reliability of road to be always in service in all weather conditions.
3. The RNAI model can be transferred and applied to other countries or regions.
4. The concept of equity indicates that the accessibility should not be necessarily the same, but its distribution should be relatively uniform across a country.
5. For levelling up the accessibility rating, e.g. from low into a medium of very high level, road network not only needs to be maintained but also needs to be managed by considering

the scenario of upgrading gravel roads into sealed roads and expanding the road network in order.

6. Road condition (C) is the most sensitive parameter for maintaining accessibility levels.
7. Expanding the road network by building a new road(s) is the most straightforward option to level up accessibility.
8. When all public services and activity centres have been connected, the new roads are suggested to be built as alternatives for vulnerable roads, i.e. roads that located in areas prone to extreme weather events.

B. Application of the RNAI Model

1. Accessibility model (RNAI) can deal with climate change and extreme weather.
2. Accessibility in Indonesia can be controlled using the existing Indonesian maintenance standards (IRMS).
3. The Indonesian maintenance standards (IRMS) were tested and found adequate to deal with climate change, but the gravel road maintenance standards should be enhanced to give an optimal accessibility level.
4. The maximise dIRI was found to be the most appropriate optimisation method in HDM-4 that gives optimum accessibility and road performance for 20 years analysis period.
5. Precipitation is the most significant weather parameter that affects the overall road network condition and accessibility level in Indonesia.
6. The impact of climate change on accessibility will be minimum when the increased parameter(s) remained in the same climate zone, but it will become significant when the zone shifts.
7. The higher the accessibility target, the higher is the required budget for road maintenance and development.

8. In the Kalimantan Selatan province, the road managers required 4.42 trillion IDR budget per km to sustain the current accessibly level over the next 20 years period.
9. In the first year of the analysis, to improve accessibility from low to moderate levels, the road managers required almost double (95.04%) the investment budget needed to maintain the accessibility level in Kalimantan Selatan province
10. In Kalimantan Selatan province, to preserve the current accessibility under climate change scenarios, the maintenance budget must increase by 8.4% for the first five-years and 16.56% for the twenty-years of analysis.
11. The initial objective of accessibility management should be set to minimise the disparity of the accessibility level by optimising the existing road assets. When extra budget is available, the accessibility can level up further by building a new road(s).
12. The road managers should reserve an extra budget for emergency roadworks to anticipate the uncertainty and severity of extreme weather events.
13. In the Kalimantan Selatan province, the impact of 5% road damage due to EWE scenario increases the road maintenance budget up to 8.26% during the first 5-year period of analysis.
14. A high disparity in accessibility hampers social-economic development and threatens national integrity.

C. The Use of HDM-4 Tool

1. The existing road asset management tool (HDM-4) can be used to deal with climate change but not to simulate extreme weather events, i.e. a sudden changes of climate parameters in the short-term and for a specific period.
2. By not altering the current HDM-4 road deterioration model, the default method for inputting climate parameters, i.e. static climate input (SC) method, was found more

appropriate to represent and simulate the potential impact of climate change on road condition than the dynamic climate (DC) input method.

3. The HDM-4 inputs should be adjusted to represent the climate change scenario (directly) and extreme weather events (indirectly).
4. In the HDM-4 simulation, extreme weather events can be simulated by assuming the road condition is in a terminal condition (structural damage) to represent the worst-case impact scenario.

D. Data Issue

1. The existing Indonesian road data sets are adequate for strategic studies on accessibility, but better quality of data is required for accessibility studies on programming or project levels.
2. The HDM-4 tool required massive data to simulate the overall condition of road networks.
3. The RNAI model must still be calculated manually using a spreadsheet outside the HDM-4 software.

10.2 Further Work

The accessibility model developed in this research is focused on road infrastructure-based parameter and used developing countries as the case study. It is felt, therefore, that further work may explore and address the following aspects:

1. Implement the accessibility model for managing all provinces in Indonesia.
2. Expand the use of the RNAI model at the programming or project level of road asset management.
3. Improve climate zone modelling in HDM-4.

4. Construct an accessibility model program to be used as an add-in tool in HDM-4 software so that the accessibility index (RNAI) can be generated automatically (replacing the manual or spreadsheet work outside the HDM-4).
5. Consider various types of pavement (e.g. penetration macadam, concrete pavement and modular pavement including brick or concrete block) and preventive roadworks maintenance (e.g. seal coating, chip seals or slurry seals).

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APPENDIX A

ACCESSIBILITY REVIEW

A.1 Definition of Accessibility

Various definition of accessibility based on literature review are as follows:

a. "the potential of opportunities for interaction" (Hansen, 1959).
b. "the inherent characteristic (or advantage) of a place with respect to overcoming some form of spatially operating source of friction, for example, time and/or distance" (Ingram, 1971).
c. "the ease with which any land-use activity can be reached from a location using a particular transport system" (Dalvi and Martin, 1976).
d. "the freedom of individuals to decide whether or not to participate in different activities" (Burns, 1979).
e. "the benefits provided by a transportation/land-use system" (Ben-Akiva and Lerman, 1979).
f. "the ease and convenience of access to spatially distributed opportunities by a choice of means of transport" (U.S. Department of the Environment, 1996).
g. "a function of the mobility of the individual, of the spatial location of activity opportunities relative to the starting point of the individual, and of the times at which the activities are available" (Odoki et al., 2001).
h. "the serviceability of a link/route/road network describes the possibility to use that link/route/road network during a given time period"(Berdica, 2002).
i. "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)" (Geurs and Wee, 2004).
j. "the quality or characteristic of something that makes it possible to approach, enter, or use it" (http://dictionary.cambridge.org).
k. "the quality of being able to be reached or entered" (www.oxforddictionaries.com).

A.2 Measurement of Accessibility Model

Various measurement of accessibility based on literature review are as follows:

1. Hansen Accessibility Index

$$AI_i = \sum_{j=1}^{n} O_j \ f(C_{ij}) \qquad \text{Equation A.1}$$

where:

AI_i = accessibility Index for location i

O_j = number of opportunities of the considered type in zone j, e.g. number of job, shopping, school, etc.

$f(C_{ij})$ = impedance function, i.e. travel distance, time, or cost from i to j

2. Separation Opportunity Measurement

$$A_{ij} = f(C_{ij}) \qquad \text{Equation A.2}$$

where:

A_{ij} = accessibility from location i to location j

$f(C_{ij})$ = travel impedance from location i to location j.

3. Cumulative Opportunities Measurement

Using the cumulative opportunities measurement approach, $f(C_{ij})$ in Hansen accessibility index is set as 1 if $C_{ij} \leq T$ and 0 otherwise.

$$A_{i,T} = \sum_{j=1}^{n} O_{j,T} \qquad \text{Equation A.3}$$

Where:

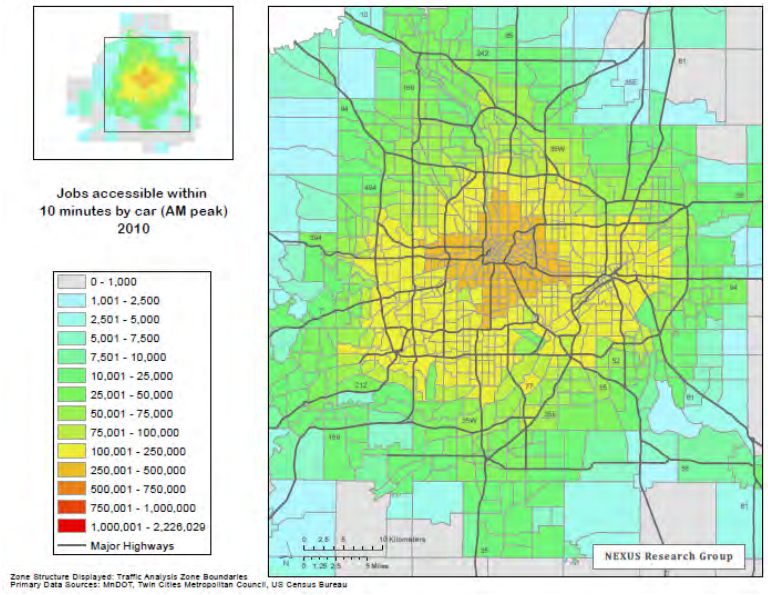
$A_{i,T}$ = Cumulative opportunity accessibility from a zone (i) within T travel time.

T = the travel time threshold for counting the number of opportunities.

$O_{j,T}$ = number of opportunities in zone (j) which located within T travel time from a zone (i), e.g., number of job, shopping, school, etc.

j = all possible area/location covered within T travel time from zone (i).

Example, jobs accessibility within 10 minutes by car in the metropolitan area is measured as number of jobs that can be reached within 10 minutes by car in morning peak hours (see **Figure A.1**).



Source: Owen and Levinson (2012)

Figure A.1 Job accessibility using opportunity measure

4. Weighted Opportunities Accessibility Measurement (Gravity Model)

   a) Basic gravity model measurement

$$g_{ij} = \frac{P_i \; P_j}{C_{ij}^2} \qquad \text{Equation A.4}$$

   where

   g_{ij} = potential travel/interaction (gravity) between location i and j

   P_i = population of location/city i

   P_i = population of location/city j

   C_{ij} = travel cost (time or distance) from city i to city j

   b) Accessibility Index based on weighted opportunity

   In this measurement, opportunities in destination are weighted by their proximity cost from origin.

$$A_{i,gw} = \sum_{j=1}^{n} O_j \; {C_{ij}}^{-2} \qquad \text{Equation A.5}$$

   where

   $A_{i,gw}$ = Accessibility index for location i using gravity weight based opportunity

   O_i = Opportunity in location/area j

   C_{ij} = travel cost (time or distance) from city i to city j

5. IRAP (Integrated Rural Accessibility Planning)

a) IRAP type-1 (Accessibility Index)

This type measure accessibility measure number of household within a village or sub-village then weighted it by average villagers' travel time to travel from their household to nearest specific basic need, service or location, i.e. water, school, market, hospital/medical clinic. Accessibility index range from zero to unlimited value depending on maximum value of travel time and number of household. The higher value of Accessibility Index (AI), the less accessibility level perceived by the villagers. Accessibility Index can be calculated following equation:

$$AI = HH \times TT \qquad \text{Equation A.6}$$

Where:

AI : accessibility index

HH : number of households

TT : average travel time (minutes) from household to certain service or destination

For example: village1 has 200 households and it takes, on average, 30 minutes to travel from household to the nearest school. The Accessibility Indicator is calculated as AI = 200 x 30 = 6,000 for village 1. Afterward, the accessibility index (AI) value can be compared to other travel purpose AI value in the same village or compared to AI value from other village with the same travel purpose (see **Table A.1**).

Table A.1 Example calculation of IRAP Accessibility Index

village name	number of house hold	average travel time based on purpose (minutes)		Accessibility Index (AI) based on travel purpose	
		education	water	education	water
(a)	(b)	(c1)	(c2)	(b x c1)	(b x c2)
Village 1	200	30	50	6,000	10,000
Village 2	700	25	70	17,500	49,000
Village 3	5000	10	2	50,000	10,000
Village 4	1200	15	1	18,000	1,200

b) IRAP type-2 (Village Accessibility Score)

The Accessibility by village score concept stressed on local people participatory. It is done by taking in depth community meeting and household survey to assess the basic need of accessibility based on villagers' preference. In this case, the accessibility definition should be clear and refers to specific service location such as access to market or access to school. Based on the assessment from community meeting, a facilitator help villager to resume the preferred accessibility indicators and undertaking household survey or another community meeting to get average value for the indicator value based on

existing condition. Afterward, villagers or village representatives are asked to give a weighting factor based on their preference. Accessibility score calculation is done following **Equation A.7**. Accessibility score range from 0 (best access) to unlimited value (worst access).

$$VAS = \sum_{i=1}^{n} I_v \times I_w \qquad \textit{Equation A.7}$$

Where:

VAS: Village accessibility score

n : number of accessibility indicator for specific sector or travel purpose

I_v : Indicator value; value of existing village condition based on specific accessibility indicator classification

I_w : Indicator weight; importance level of an indicator component based on average villagers' preference.

For example: there is an accessibility measure in certain village with 3 sub-village, named A, B and C. The IRAP measure accessibility level of the sub-village to access education. Based on participatory survey, there are 6 indicators (see **Table A.2**) with 5 indicator weight (**Table A.3**) used to measure it. The calculation result shows that sub-village B has the biggest accessibility score (see **Table A.4**). It means sub-village B has the worst accessibility problem for education sector. Hence the development should prioritize to counter accessibility problem in that sub-village.

Table A.2 Indicator component and indicator value of accessibility for education sector

Indicator component		Indicator value for education		
No	Name	1	2	3
1	Number of student	< 50	50-100	>100
2	Number of teacher	<6	6-12	>12
3	Transport mode	private vehicle or walk <1 km	public transport or walk 1-2 km	walk > 2km
4	Distance	< 1 km	1–2 km	> 2 km
5	Travel time	< 15 minutes	15-30 minutes	> 30 minutes
6	Travel cost	< Rp. 500	Rp.500-Rp.1000	> Rp.1000

Table A.3 Indicator weight of accessibility for education sector

No	Importance level	weight
1	Not-importance	1
2	Little important	2
3	medium	3
4	fair	4
5	very	5

Table A.4 Accessibility score calculation for education sector

Name of sub-village	Indicator value (I_v)						Indicator weight (I_w)						Accessibility score = $\sum I_v * I_w$	Priority
	1	2	3	4	5	6	1	2	3	4	5	6		
A	3	1	2	2	2	3	3.67	3.00	3.33	3.67	3.67	4.00	47.35	2
B	2	2	3	1	3	3	4.33	3.67	3.67	3.33	4.00	4.33	55.33	1
C	1	3	1	3	2	2	3.67	3.33	3.33	3.00	3.00	3.67	39.33	3

6. The Accessibility/Remoteness Index of Australia (ARIA)

   Accessibility/Remoteness Index of Australia (ARIA) calculates remoteness as accessibility to service centers based on road distances. The calculation can be done either based on populated locality or based on each square km of "grid-cell" area following **Equation A.8.** ARIA assume that general post office (GPO) as the center point of service centers (km zero). Consequently, it is needed to calculate physical road distance between the assessed location and GPO location of each nearest service center category. ARIA score ranging from 0 to 12 with the maximum score for each category is 3.0. The threshold 3.00 is exist to maintain the score range, e.g. 0-12 for ARIA, unless the ARIA index may reach more than 12 as the maximum index value.

$$ARIA\ (x,y) = \sum_{L} min\left\{3, \frac{d_L(x,y)}{\bar{d}_L}\right\} \qquad \textit{Equation A.8}$$

Where:

d_L : road distance from origin to nearest service center with "L" category (km)

x : origin, a location which is Accessibility index is calculated

y : destination, nearest location of service category

L : service center category (A, B, C, D)

$\bar{d}_L$: average national road distance to reach service center with "L" category (km)

The calculation steps to do so are described as follows:

step 1. Divide origin-destination (area based) or alternatively divide network into one square km grid of area (continuum based)

step 2. Identify all service center (category A to category D).

step 3. Measure the nearest distance between assessed grid to each service center category (A, B, C, and D). If the nearest distance of lower service center (e.g. service center D) is farther than the nearest distance of higher service center (e.g. service center C), the nearest distance value for the lower service center is equal to the higher service center distance

value (i.e. distance to C = distance to D). when the assessed location is within the service center "X", the nearest distance value for category "X" become zero.

step 4. Compute ratio value by dividing the nearest distance value by national average value for each category. The ratio value for each component/category is capped at a value of 3.0 as the maximum.

step 5. The ARIA score is the summation of each category, ranging from 0 to 12 for ARIA and 0 to15 for ARIA+.

The example of ARIA+ calculation, as a case study, can be seen in **Table A.5** together with the detail calculation described in **Table A.6**. The ARIA+ score is 8,6 therefore that area can be categories as a remote area with low level accessibility to reach services.

Table A.5 Spatial information of location that assessed using ARIA^{+} index

Name of service center	Service Centre Category	Distance from the assessed grid (km)
Y1	A	2,800
Y2	B	210
Y3	C	300
Y4	D	94
Y5	E	102

Table A.6 Example of ARIA+ Index calculation

Service Centre Category	Nearest distance from assessed 1km2 grid		National average distance for each category	ARIA+ score
	Name of service center	distance		
A	X	2,800	420	2,800/420 = 6.67 → = 3 ***
B	Y	210	215	210/215 = 0.98
C	Y*	210*	132	210/132 = 1.59
D	Z	94	85	94/85 = 1.11
E	Z**	94**	48	94/48 = 1.96
ARIA Score = 3+0.98+1.59+1.1+1.96 = 8.6 → remote area/low accessibility				

** There were no Category C Service Centers closer to assessed grid than "Y2", so "Y2" functions as both the closest Class B and Class C center.*
*** There were no Category E Service Centers closer to assessed grid than "Y4", so "Y4" functions as both the closest Class D and Class E center.*
**** exceeds threshold 3, use the threshold value as the maximum score = 3.00.*

7. Perceived Opportunities Accessibility Measurement

a) Maximum utility

This measurement refers to (Ben-Akiva and Lerman, 1979) to measure utility value received by individual at location i from opportunity in location j which is described as follows:

$$A_n = E\left[max\left(V_{ij} + \beta c_{ij} + \varepsilon_{ij}\right)\right] \qquad \textit{Equation A.9}$$

Where:

A_n = Accessibility for individual n

V_{ij} = utility or value received by making a trip from location i to location j

β = a cost sensitivity parameter

c_{ij} = trip cost to travel from location i to location j

ε_{ij} = a random term

b) Integrated accessibility-benefits mode

This measurement refers to Odoki et al. (2001) for estimating the value of accessibility benefit.

$$BM = exp\left[-\left(\frac{m}{\alpha I} + \frac{1}{v}\right)2x_k + \right][c\ \rho\ \omega]_{jk} h^{\tau}\left[\tau - \frac{2x_k}{v}\right]^{\gamma} \qquad \textit{Equation A.10}$$

Where:

BM = maximum benefit

m = monetary income

αI = monetary value of time for individual per hour

v = average speed of travel

τ = time budget available between coupling constraints

x = travel distances

k = travel destination

ω = weighting factor

ρ = the level of activity

γ = income

c) Changing in accessibility value

This method is the simplest method to calculate accessibility benefit. The benefit is measured from changing in accessibility value by comparing before and after scenario. The accessibility measurement may use any accessibility measurement technique, e.g. measured by generalized cost, cumulative opportunity or weighted opportunity. The example steps to measure changing in generalized cost can be described using a case study from Taylor et al. (2006) as follows:

step 1. Prepare the network Origin-Destination (O-D) matrix data.

If there is no O/D matrix data, use the newton method (simple gravity model, see *Equation A.4*) from population and distance data (see **Table A.7**) to define the network O/D pairs. The result is shown in **Table A.8**.

Table A.7 Number of populations and travel distances varies city in Australia (2001)

City	Adel	Bris	Can	Dar	Mel	Per	Syd
population	1,002,127	1,508,161	339,727	71,347	3,160,171	1,176,542	3,502,301
Travel Distance via national road (km)							
Adel	-	1,985.65	1,167.53	2,622.94	722.51	2,691.74	1,341.89
Bris		-	1,004.55	3,102.96	1,536.12	4,643.25	796.07
Can			-	3,756.33	636.23	3,828.58	235.48
Dar				-	3,345.45	3,465.77	3,873.15
Mel					-	3,414.25	810.60
Per						-	3,999.49
Syd							-

Source: Taylor et al. (2006)

Table A.8 Origin-Destination (O-D) matrix result based on gravity model (g_{ij})

O-D		Destination location (city name)						
		Adel	Bris	Can	Dar	Mel	Per	Syd
Origin location (city name)	Adel	0	383,323	249,756	10,393	6,066,604	162,729	1,949,137
	Bris		0	507,732	11,176	2,019,798	82,302	8,334,867
	Can			0	1,718	2,652,237	27,269	21,457,320
	Dar				0	20,145	6,988	16,657
	Mel					0	318,954	16,844,218
	Per						0	257,603
	Syd							0

step 2. Compute normalized weighting factor (w_{ij}) for all O/D pairs

$$w_{ij} = \frac{g_{ij}}{\sum_{ij} g_{ij}} \qquad \textit{Equation A.11}$$

Table A.9 weighting factor result

O-D		Destination location (city name)						
		Adel	Bris	Can	Dar	Mel	Per	Syd
Origin location (city name)	Adel	0	0.62	0.41	0.02	9.88	0.27	3.18
	Bris		0	0.83	0.02	3.29	0.13	13.58
	Can			0	0.00	4.32	0.04	34.96
	Dar				0	0.03	0.01	0.03
	Mel					0	0.52	27.44
	Per						0	0.42
	Syd							0

step 3. Calculate travel time with link removal scenario

step 4. Calculate changing in travel time before and after disruption or link removal (Δt_{ij}^{e})

step 5. Calculate the generalized cost impact for each link removal $\Delta t(e)$

$$\Delta t(e) = \sum_{ij} w_{ij}\, \Delta t_{ij}^{e} \qquad \textit{Equation A.12}$$

8. Competition Opportunities Accessibility Measurement

This measurement refers to equation from Geurs and Eck (2001) that developed based on Weibull (1976) measurement.

1. Competition based on origin locations

This measurement is done by give correction factor to basic accessibility measurement either only by direct competition (competitor located in the same destination area) or also indirect competition, i.e. competitor located not only in destination zone k but also competitor located at surrounding zone k area.

$$A_{CF} = A_i\, CF \qquad \textit{Equation A.13}$$

$$CF_0 = \frac{\sum_{j=1}^{n} D_j\, F(d_{ij})}{\sum_{j=1}^{n} O_j\, F(d_{ij})} \qquad \textit{Equation A.14}$$

$$CF_l = \frac{\sum_{j=1}^{n} D_j\, F(d_{ij}) * CF_0}{\sum_{j=1}^{n} O_j\, F(d_{ij})} \qquad \textit{Equation A.15}$$

Where:

A_{CF} = potential accessibility of area i , corrected for competition

A_{i} = potential accessibility of area i

CF = competition factor, either direct competition (CF_0) or also taking indirect competition (CF_{l})

D_{j} = the number of opportunities

O_{j} = the number of inhabitants (origin)

$\mathrm{F}(\mathrm{d_{ij}})$ = a distance decay function

Another equation comes from Joseph and Phillips (1984) known as local quotient (see Equation A. 16). in theory, the value range from zero to infinite but in reality the value is less than 5, normally ranging from 0 to 2. A location quotient greater than 1.0 ($LQ_i > 1$) means low competition, conversely, location quotient lower than 1.0 ($LQ_i < 1$) means high competition (supply is more than demand).

$$LQ_i = \frac{GP_i \;/\; P_i}{\sum_i GP_i \;/\; \sum_i P_i} \qquad \textit{Equation A. 16}$$

Where:

LQ_i = location quotient for region i

GP_i = the number of general practitioners in region i

P_i = the population of region i

2. Competition based on destination locations (supplier oriented)

This measurement developed by (Joseph and Bantock, 1982) calculated by dividing supply (the number of general practitioners) reachable within a certain distance from i by the potential demand (number of people) within the catchment area of supplier (general practitioner).

$$A_i = \sum_{j=1}^{n} \left[\frac{GP_j}{\sum_{i=1}^{n} P_i F(d_{ij})} \right] F(d_{ij}) \qquad \textit{Equation A. 17}$$

Where:

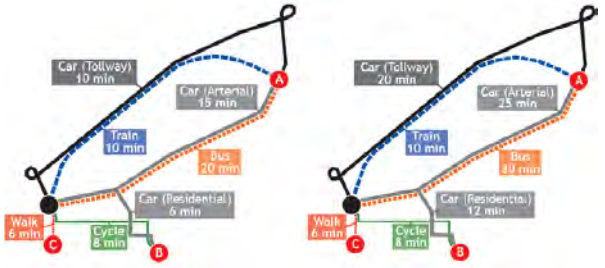
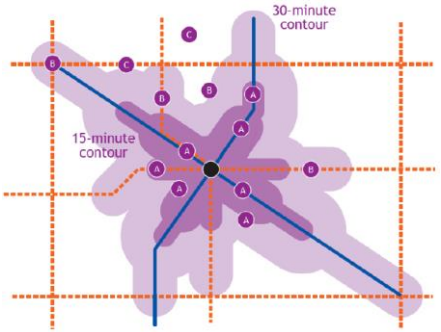
A_i = potential accessibility of area i to general practitioners

GP_j = number of general practitioner at area j within range of area i

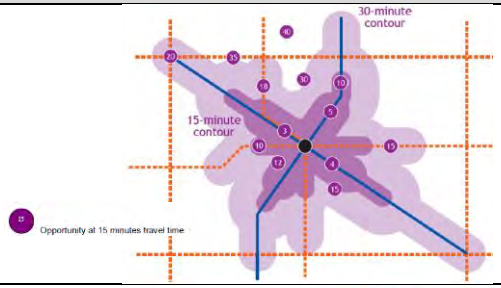
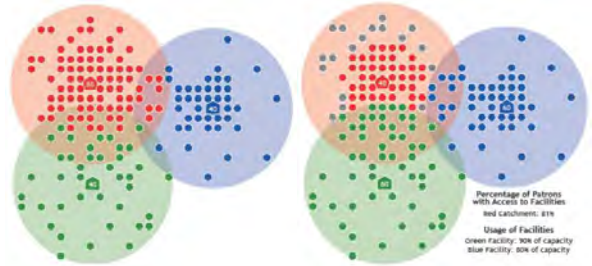
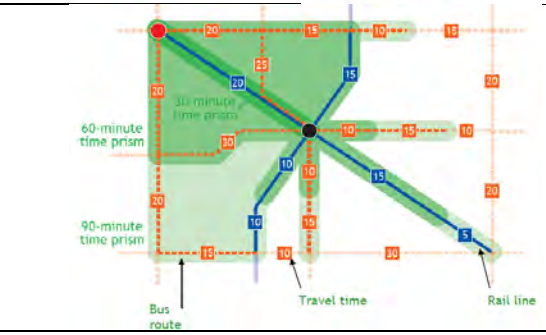
P_i = number of population within the doctor's catchment area

$F(d_{ij})$ = a function of the distance decay between i and j

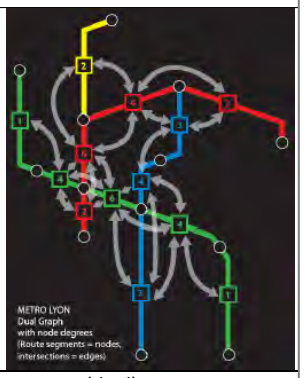
Various example measurement of accessibility

No	accessibility measures	Methodological Category	Approach / Measure	Pros & Cons	Overview
1	Spatial Separation Measures	▪ **Spatial Separation Model** (Bhat et al, 2000) ▪ **Infrastructure Measures** (Geurs & van Eck, 2001) ▪ **Travel Cost Approach** (Baradaran & Ramjerdi, 2001)	Measures **travel impediment** or **resistance** between origin and destination, or between nodes. Travel impediment measures can include: ▪ Physical Distance (Euclidean) ▪ Network Distance (by mode) ▪ Travel Time (by mode) ▪ Travel Time (by network status – congestion, free-flow etc) ▪ Travel Cost (variable user cost or total social cost) ▪ Service Quality (eg. public transport frequency)	▪ Data is generally easily available from digital mapping material and other public sources. ▪ No consideration of land use patterns and spatial distribution of opportunities.	free-flow conditions (left), and during congestion (right) 
2	Contour Measures	▪ **Contour Measures** (Geurs & van Eck, 2001) ▪ **Cumulative Opportunity Model** (Bhat et al, 2000)	Defines catchment areas by drawing one or more **travel time contours** around a node, and measures the number of opportunities within each contour (jobs, employees, customers etc).	▪ Incorporates land use and attends to infrastructure constraints by using travel time as indicator for impediment. ▪ Definition of travel time contours may be arbitrary and does not differentiate between activities and travel purposes. ▪ Methodology cannot capture variation in accessibility between activities within the same contour.	

Various example measurement of accessibility

No	accessibility measures	Methodological Category	Approach / Measure	Pros & Cons	Overview
3	Gravity Measures	▪ **Gravity Model** (Bhat et al, 2000) ▪ **Potential Accessibility Measure** (Geurs & van Eck, 2001)	Defines catchment areas by measuring travel impediment on a **continuous scale**.	▪ More accurate representation of travel resistance than in contour measure, but tends to be less legible. ▪ Does not differentiate between travel purposes and individual drivers for travel.	
4	Competition Measures	▪ **Competition Measures** (van Wee, Hagoort and Annema 2001) ▪ **Joseph & Bantock Measure** (1982) ▪ **Inverse Balancing Factor Model** (Geurs & van Eck, 2001)	▪ Incorporates **capacity constraints of activities and users** into accessibility measure. ▪ May make use of any of the preceding three models.	Provides a regional perspective on accessibility.	
5	Time-Space Measures	▪ **Time-Space Measures** (Bhat et al, 2000 and Geurs & van Eck, 2001) ▪ **Person-Based Measures** (Geurs & van Wee, 2004)	▪ Measures travel opportunities within **pre-defined time constraints**.	▪ Well-suited to examine trip chaining and spatial clustering of activities. ▪ Usually requires project-specific user surveys, limiting the geographical range and compatibility of data.	

Various example measurement of accessibility

No	accessibility measures	Methodological Category	Approach / Measure	Pros & Cons	Overview
6	Utility Measures	▪ **Utility Measures** (Bhat et al, 2000 and Geurs & van Eck, 2001) ▪ **Utility Surplus Approach** (Baradaran & Ramjerdi, 2001)	Measures **individual or societal benefits** of accessibility. Indicators can include: ▪ **Economic utility** (to the individual, or to the community) ▪ **Social or environmental benefits** (eg. social inclusion, greenhouse effects) ▪ **Individual motivations** of travel (by activity or travel purpose) ▪ **Option** and **non-user benefits** of transport infrastructure	▪ The empirical link between infrastructure provision and economic performance is tenuous and contested. ▪ The indicator can analyse existing motivations of travel, but cannot anticipate feedback effects between land use and travel patterns, or future behaviour patterns of users.	
7	Network Measures	**Network Measures: Multiple Centrality Assessment** (Porta et al 2006a, 2006b)	Measures **centrality** across entire movement networks. Networks can be represented by: ▪ the **primal approach** (networks are understood as intersections connected by route segments) ▪ the **dual approach** (networks are understood as route segments connected by intersections)	▪ More intuitive, and allows for the incorporation of a travel impediment measure in the network analysis. ▪ Clearly captures the topological form of a network, and can be used to assess its spatial legibility	 (primal)  (dual)

Various example measurement of accessibility

No	accessibility measures	Methodological Category	Approach / Measure	Pros & Cons	Overview
8	Integrated Rural Accessibility Planning (IRAP)	Rural Accessibility – location and travel purpose based	▪ Model 1: by travel time & no. of household ▪ Model 2: adding village preference for weighting factor at indicator value	▪ Taking account community participatory make decision support easy to accept by community ▪ Distance and number of services become key indicator ▪ Tends to abuse and loss in equity by taking account number of household. It will discriminate village with small household number except village categorised by no of household.	$Access = f\,(distance, time, cost)$ Model 1: AI = HH x TT Model 2: $\sum^{n} average\ Indicator\ weight \times indicator\ value$ 

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APPENDIX B

CASE STUDY

B.1 Data Requirement of This Research

Based on the research framework and method, the required data to conduct this research are as follows:

Data Collection

Type of Data	Method	Source
Road network and detail sub-network Road network map IRMS (national road database)	Secondary data collection	Road authority, i.e., ministry of public work
Design standard Indonesian road design standard	Secondary data collection	Road authority, i.e., ministry of public work
Maintenance standard Intervention level Typical maintenance work	Secondary data collection	Road authority, i.e., ministry of public work
Road responsibility (asset ownership) National road Province Local road	Secondary data collection	Road authority: ministry of public work, Dinas PU Province, Dinas PU Regency
Previous Accessibility model	Literature review interview	Paper, journal, report Road authority
Climate and Extreme Weather Historical data Climate change projection	Literature review Secondary data collection	Paper, journal, report BMKG Indonesia
Regional economic development Gross Regional Domestic Product Poverty	Secondary data collection	BPS Province, BPS Regency

B.2 Maps of Indonesia and Kalimantan Selatan Province

B.2.1 Map of Indonesia



B.2.2 Map of Kalimantan Selatan province



B.3 Characteristic or Road Asset in Indonesia

Characteristics of road asset in Indonesia based on road status (ownership)

Typical characteristic	Road status (authority) [b]		
	National road	Province road	Regency road
Road class	highway	road	street
Journey type	Long distance	Medium distance	Short/medium distance
Traffic	High/medium	Medium	Medium/low
Speed	>= 80 km/h	40-80km/h	50 km/h
Number of lane and direction [a]	6/2, 4/2, 2/2	4/2, 2/2	4/2, 2/2, 1/2
Lane width	3.5-3.75 m	3.5 m	3.25-3.5 m

a. typical road: 6/2 means the road has 6 lanes for 2 directions (3 lanes for each traffic direction)
b. based on spesifikasi penyedia prasarana (Undang-Undang RI nomor 38 tahun 2004) and Indonesian Ministry of Public Works (2012)

B.4 Road Asset Maintenance Standards in Indonesia

The strategic level of maintenance standards Indonesia (IRMS)

Indonesia road condition category (IRMS)

Surface type		**Maximum roughness (IRI, m/km)**			
		good	fair	poor	bad
Sealed	Cement concrete	4	10	12	>12
	Asphalt mix	4	8	12	>12
	Pen Macadam	8	10	12	>16
Un-sealed	Gravel, earth road	10	12	16	>16

Strategic level of maintenance standards (IRMS)
for Bituminous Road in Indonesia

Roadwork category	Thresholds [a]				
	Roughness (IRI, m/km)	Interval (years)	Surface Damage (visual survey)		
			SDI [b]	(%)	Severity
Routine	< 4	n/a	<50	< 6	no damage
Periodic	3.5-8	≥ 5	<150	6 to 11	light
Rehabilitation	8 to 12	≥ 5	n/a	11 to 15	medium
Reconstruction, Structural Improvement	> 12	≥ 10	n/a	> 15	Severe

a. Based on 'Pedoman konstruksi & bangunan' No.01-04/P/BM/2011 (Indonesian Ministry of Public Works, 2011) and Network Analysis Maintenance (NAM) standards in Indonesian Integrated Road Management System (IRMS) tool.
b. Surface Distress Index (SDI)

Indonesian IRMS maintenance standards

Scenario	Road surface category		
	Bituminous road		Gravel road
Do Minimum	▪ Edge repair ▪ Patching	▪ Reconstruction	▪ Grading ▪ Gravel resurface
IRMS	▪ Edge repair ▪ Patching ▪ Crack sealing ▪ Drainage	▪ Thin overlay ▪ Thick overlay ▪ Reconstruction ▪ Vegetation control	▪ Grading ▪ Spot re-gravel ▪ Gravel resurface

B.5 The HDM-4 Input

B.5.1 Road network representative

In the strategic level of analysis, road networks in this research are simplified based on road status, type of pavement, traffic and roughness.

Road representative

Road status	Pavement Type	Traffic (T)	Roughness (R)
(N) National (P) Province (R) Regency	(A) Asphalt-Paved-	(1) High	(1) Good (2) Fair (3) Poor (4) Bad
		(2) Medium	
		(3) Low	
	(G) Gravel Unpaved	(5) Low	
		(6) Very Low	

Example: R2T2C3= gravel road with medium traffic in poor road condition

The example of road matrix representative based on the above category are shown in the following table.

Categorized length of the road network
in Kalimantan Selatan province in the year 2014 (km)

Surface Type	Road status	Traffic Category	Condition [a]				Total
			Good	Fair	Poor	Bad	
Bituminous (Asphalt)	National	[T1] High	231	16	-	-	247
		[T2] Medium	531	42	10	-	583
		[T3] Low	326	24	4	3	357
	Provincial	[T1] High	28	12	15	10	65
		[T2] Medium	184	96	24	14	318
		[T3] Low	146	61	55	56	318
	Regency/ District	[T1] High	494	387	53	24	958
		[T2] Medium	675	519	984	874	3,052
		[T3] Low	462	223	753	433	1,871
Unsealed (Gravel)	National	[T5] Medium	12	5	-	-	17
		[T6] Low	-	-	-	-	-
	Provincial	[T5] Medium	52	33	22	-	107
		[T6] Low	35	6	3	-	44
	Regency/ District	[T5] Medium	1,470	651	154	122	2,397
		[T6] Low	1,092	656	187	249	2,184
		Total Road Asset	5,738	2,731	2,264	1,785	12,518

a. based on the Indonesian Ministry of Public Works (2015) in BPS (2015).

B.5.2 Traffic category

National road (N)

Traffic Category	Traffic, AADT (vehicle per day)						
	Paved road				Unpaved road		
	Code	Range	Representative		Code	Range	Representative
High	T1	> 10,000	15,000		T4	≥ 1,000	1,000
Medium	T2	7,500 to 10,000	10,000		T5	500-1,000	750
Low	T3	≤ 7,500	7,500		T6	≤ 500	500

Provincial road (P)

Traffic Category	Traffic, AADT (vehicle per day)						
	Paved road				Unpaved road		
	Code	Range	Representative		Code	Range	Representative
High	T1	> 10,000	10,000		T4	>750	1,000
Medium	T2	5,000 to 10,000	7,500		T5	250-750	500
Low	T3	≤ 5,000	5,000		T6	≤ 250	250

Regency road (R)

Traffic Category	Traffic, AADT (vehicle per day)						
	Paved road				Unpaved road		
	Code	Range	Representative		Code	Range	Representative
High	T1	5,000 to 10,000	7,500		T4	>750	1,000
Medium	T2	2,000 to 5,000	5,000		T5	250-750	500
Low	T3	≤ 2000	2,000		T6	≤ 250	250

B.5.3 Roughness category

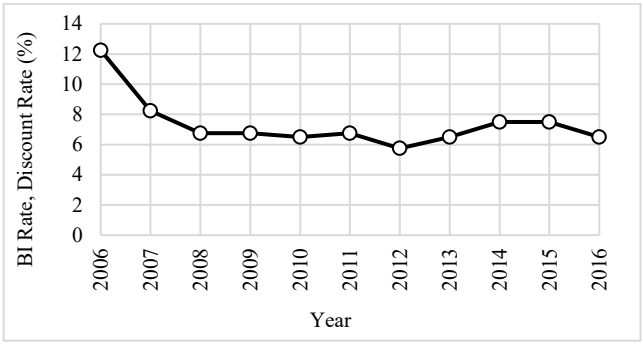
Roughness representative

Parameter		Road condition (Roughness, IRI, m/km)			
Pavement type	Category	Good	Fair	Poor	Bad
Paved (asphalt)	Code	R1	R2	R3	R4
	Range [1]	< 4	4 to 8	8 to12	> 12
	representative	3	6	10	13
Unpaved (gravel)	Code	R5	R6	R7	R8
	Range [1]	< 10	10 to12	12 to 16	>16
	representative	7	11	14	17

[1] based on IRMS

B.5.4 Discount rate

Based on the historical data, the discount rate in this research are set to be 7% per year



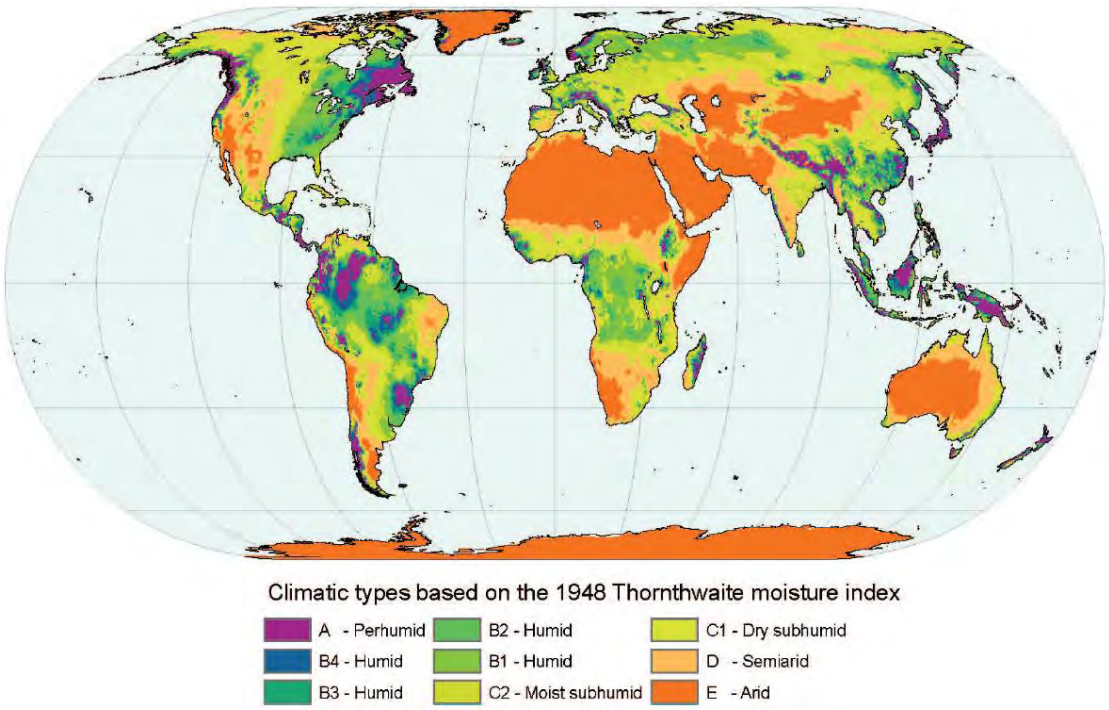
Indonesia Discount rate (After Bank Indonesia, 2017)

B.5.5 Climate parameter

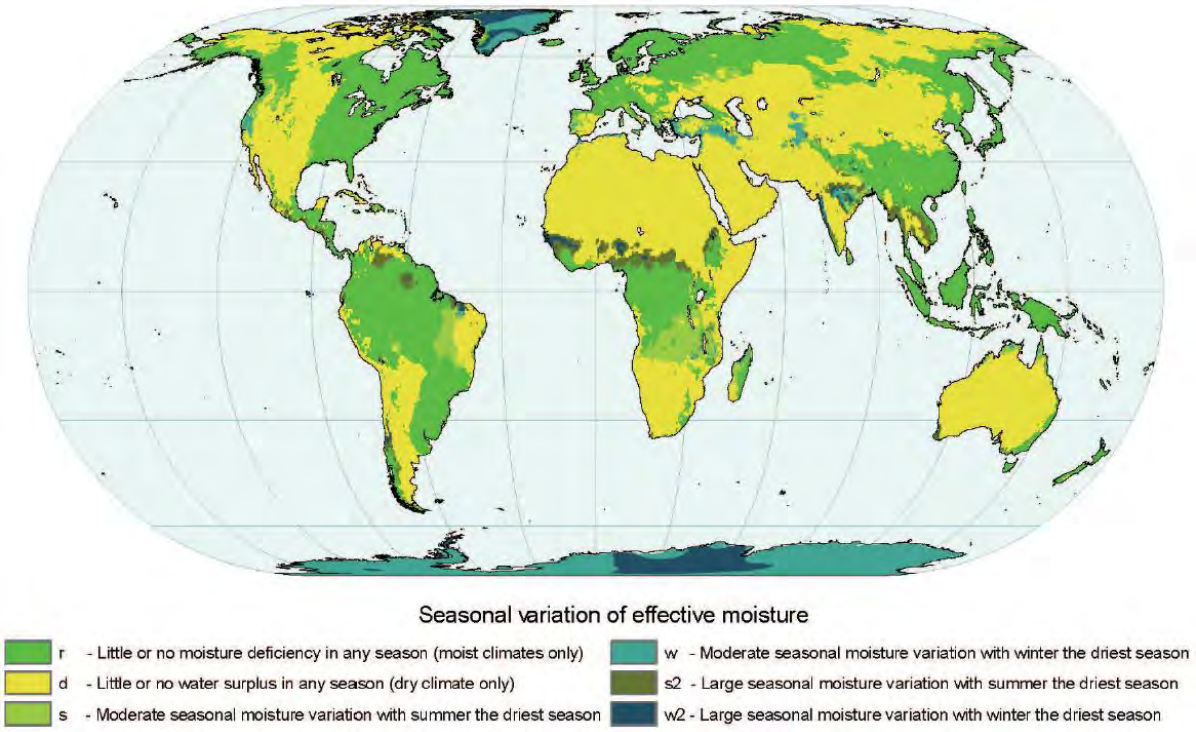
The default value of climate parameter in HDM-4 version 2

Climate factor		Climate Zone				
Precipitation	Moisture classification	Arid	Semi-arid	Sub-humid	Humi	Per-humid
	Moisture Index	-80	-40	0	60	100
	Duration of dry season [months]	10.8	9	6	3	1.2
	Mean monthly precipitation [mm]	15	50	100	175	210
Temperature	Temperature classification	Tropical	Subtropical		Temperate	
			hot	cool	cool	freeze
	Mean temperature [^{0}C]	27	22	18	12	8
	Avg. Temperature range [^{0}C]	15	17	13	15	20
	Days T>32 ^{0}C [days]	90	60	30	15	10
	Freeze Index [C-days]	0	0	0	55	220
	Percentage of Time Driven:					
	▪ On snow covered roads [0-100]	0	0	0	10	20
	▪ On Water covered roads [0-100]	20	10	15	5	10

Source: HDM-4 Manual, Morosiuk et al. (2004)

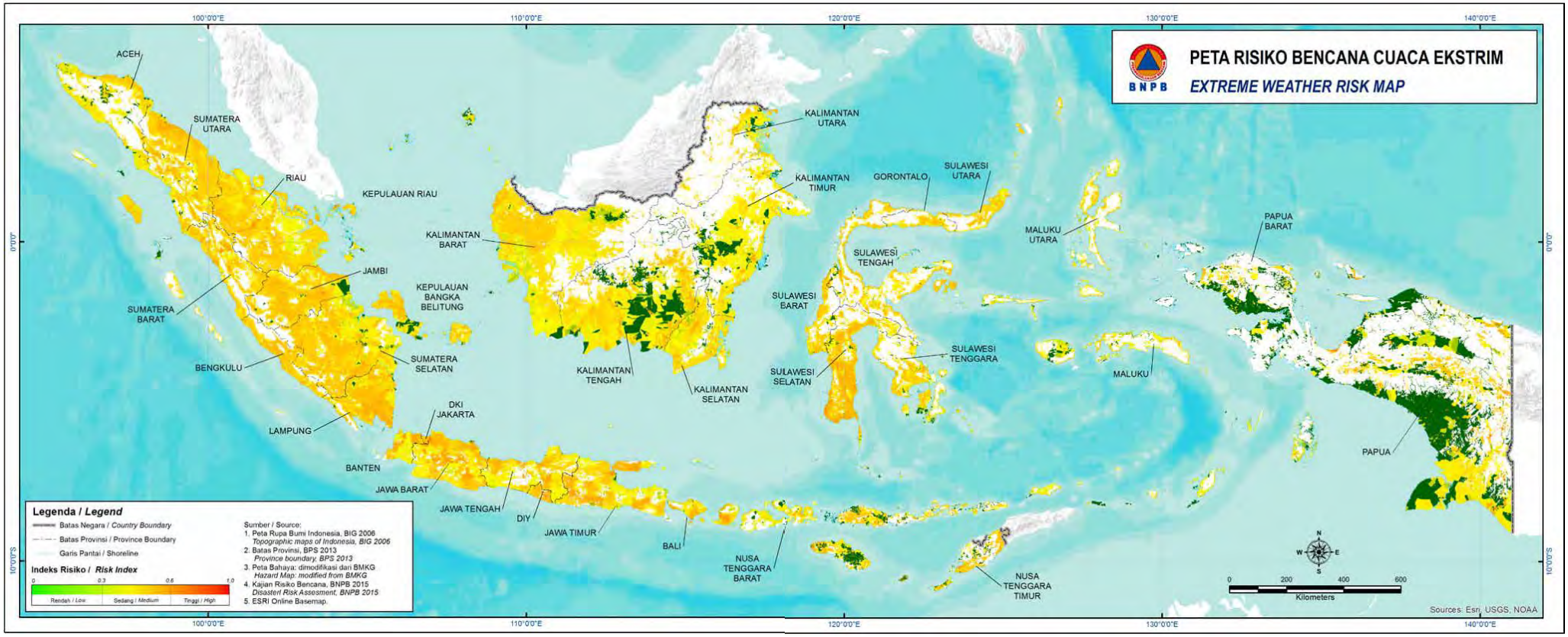


Thornthwaite moisture regions ((After Feddema, 2005)

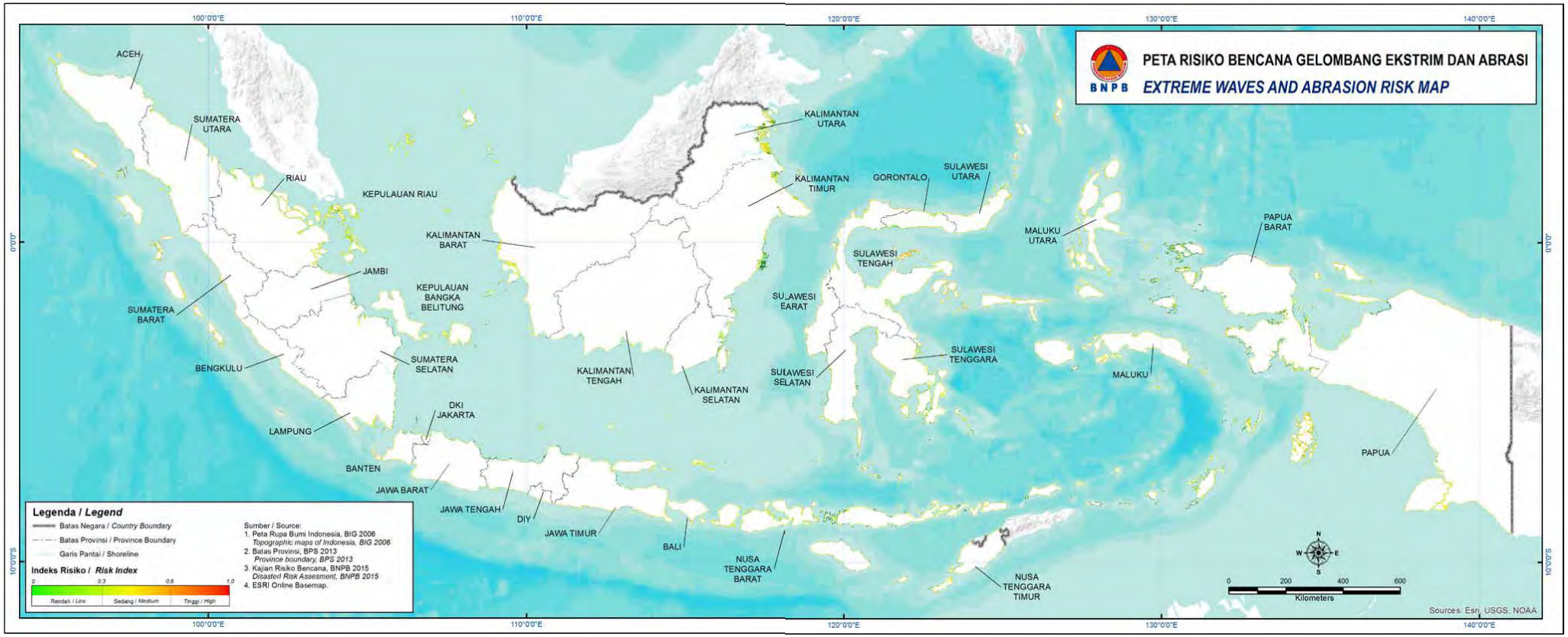


The global Thornthwaite seasonal variation of effective moisture after (After Feddema, 2005)

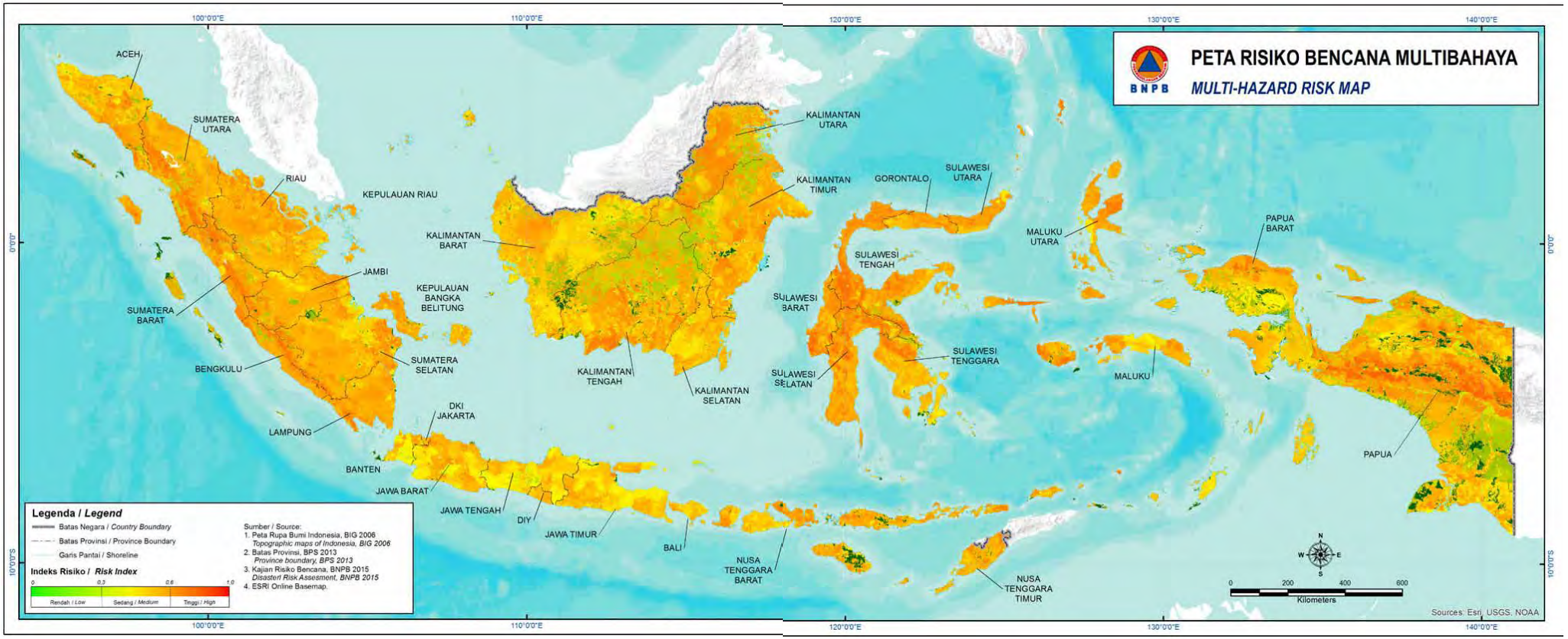
B.5.6 Disaster risk map



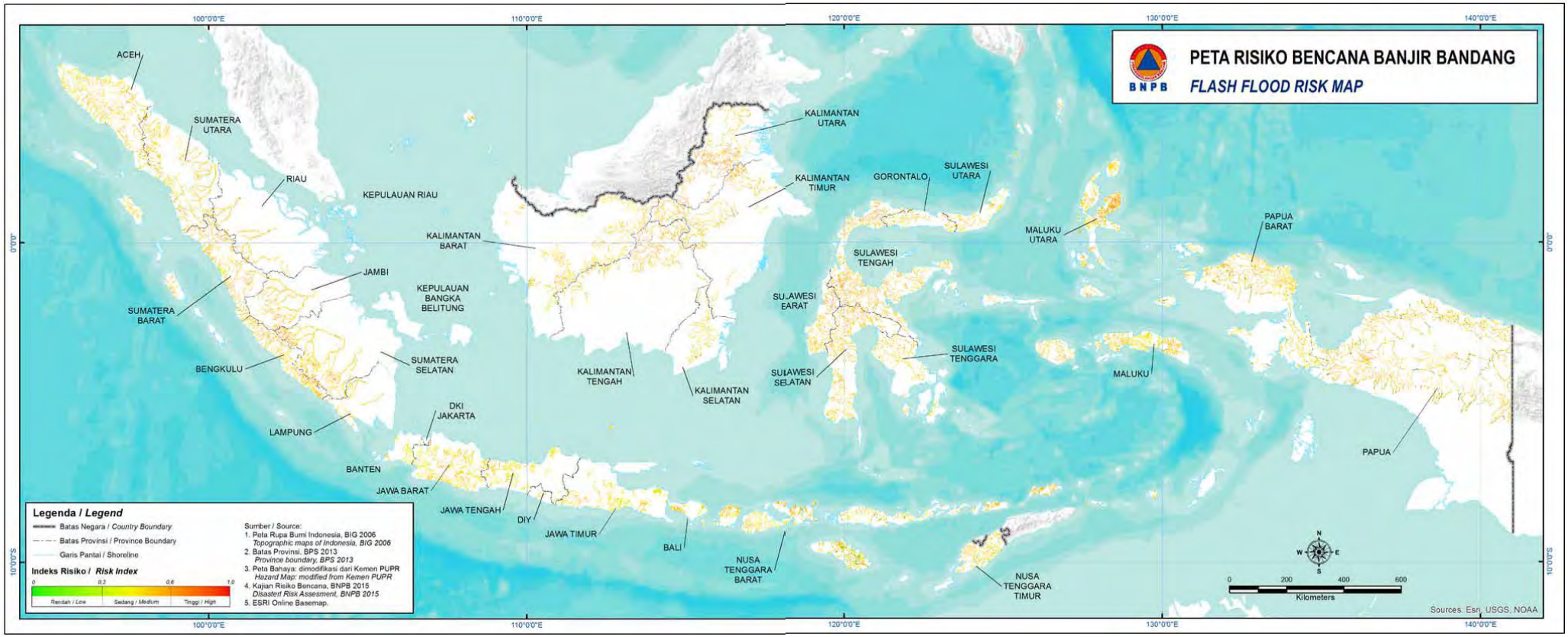
(After Amri et al., 2016)



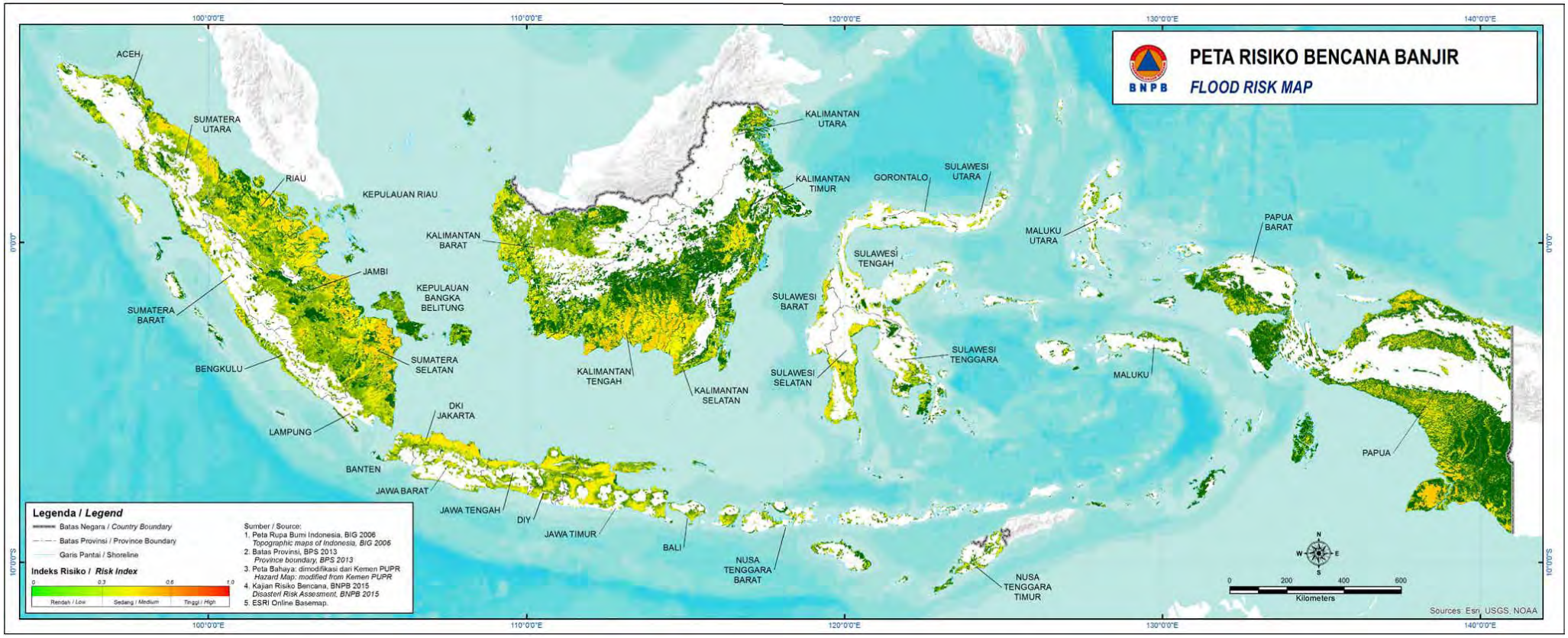
(After Amri et al., 2016)



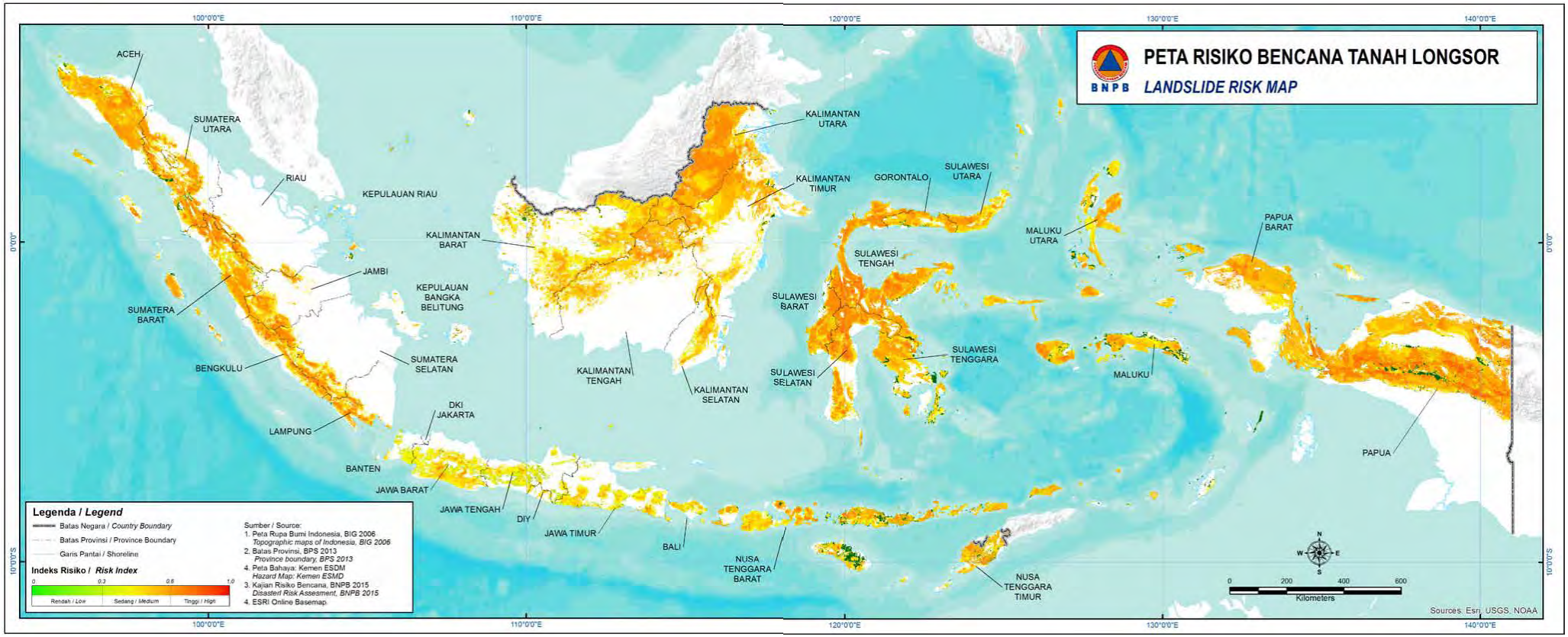
(After Amri et al., 2016)



(After Amri et al., 2016)



(After Amri et al., 2016)



(After Amri et al., 2016)

B.5.7 Roadworks activity, intervention level and cost

Roadwork		intervention level		Roadwork cost (thousand IDR)	
Category	Activity	Intervention Criteria	unit	Year 2005	Year 2014 (Projected) [a]
Routine	Edge Repair	Edge break >= 1 m2/km	m2	10	18.4
Routine	Patch Potholes	Pothole >= 1 no./km	m2	10	18.4
Routine	crack sealing	Wide Structural Cracking 10-30 & Year >=3 & Interval >=3	m2	10	18.4
Routine	drainage	DF >=4	km	700	1,286.9
Routine	Ditches, drains, cuttings & embankment	Year >=1	km	700	1,286.9
LTMP	Reh Minor - Overlay 30	IRI 3.5-8 & AADT <=5,000 & Interval >=3	m2	113	207.3
LTMP	Reh Minor - Overlay 40	IRI 3.5-8 & AADT 5,000-10,000 & Interval >=3	m2	137	251.9
LTMP	Reh Minor - Overlay 50	IRI 3.5-8 & AADT >=10,000 & Interval >=3	m2	159	292.3
LTMP	Reh Mayor - Overlay 60	IRI 8-12 & AADT <=5,000 & Interval >=5	m2	180	330.9
LTMP	Reh Mayor - Overlay 70	IRI 8-12 & AADT 5,000-10,000 & Interval >=5	m2	213	391.6
LTMP	Reh Mayor - Overlay 80	IRI 8-12 & AADT >=10,000 & Interval >=5	m2	251	461.5
LTMP	Recon LT-MT (100)	IRI >=12 & AADT <=10,000 & Interval >=10	m2	420	772.2
LTMP	Recon HT (110)	IRI >=12 & AADT >=10,000 & Interval >=10	m2	534	981.7
Unsealed Maintenance	Grading	Interval >= 180 days	km	1,000	1,838.5
Unsealed Maintenance	Spot Regravelling	Gravel thickness <=200mm & Maximum material <= 200m3/km/year	m3	25	46.1
Unsealed Maintenance	Regraveling	IRI>=10 & Gravel thickness <=150mm	m3	25	46.1
Sealing of unpaved road HT	upgrade		km	1,162,000	2,136,289.6
Sealing of unpaved road HT	upgrade		km	1,631,000	2,998,527.0
new bituminous	new bituminous		km	n/a	30,000,000.0
new gravel	new gravel road		km	n/a	7,000,000.0

B.6 The HDM-4 Calibration Factor

The HDM-4 calibration factors for Indonesia in this research are based the research from Morosiuk et al. (2002). Morosiuk is one of the developers of the HDM-4 model. He did a project about road deterioration modelling In Indonesia with aims to determine the appropriate HDM-4 calibration factor for Indonesia. The calibration factors were intended to feed the IRMS tool, the Indonesian Integrated Road Management System, which previously developed based on HDM-III model. He done his research by predicting road network performance over 10 years period using HDM-4 and compare it with actual road deterioration and performance database. Based on his research, He outlined that the HDM-4 calibration factor for Indonesia may use the following value of calibration factors.

HDM-4 Calibration set for Indonesia Indonesia (After Morosiuk et al., 2002)

Deterioration Model		Code	Calibration factor	
			Range [a]	mean
Cracking	Initiation of cracking	Kcia	0.5-0.8	0.7
	Crack progression	Kcpa	1.1	1.1
Deformation (Rutting)	Initial densification,	Krid	0.3-1.0	0.6
	Structural deformation	Krst	0.9-1.1	1.0
	Plastic deformation	Krpd	0.7-2.0	1.3
Roughness	Environmental coefficient	Kgm	Well-constructed: 1.3 HT & 2.6 M-LT Poor-constructed: 5.3 HT & 5.5 M-LT	2.6
	Potholing progression	Kgp	Well-constructed: 1.0 HT, 1.2 M-LT Poor-constructed: 1.0 HT, 1.4 M-LT	1.2

a. HT=high traffic, M-LT=medium and low traffic

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Feddema, J. J. (2005) 'A revised Thornthwaite-type global climate classification', *Physical Geography,* 26(6), pp. 442-466.

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PM PU No.03 Tahun 2012 tentang Pedoman Penetapan Fungsi Jalan dan Status Jalan.

Morosiuk, G., Riley, M. J. and Odoki, J. B. (2004) *Volume 6 - Modelling Road Deterioration and Works Effects. The Highway Development and Management Series*: The World Road Association (PIARC).

Morosiuk, G., Toole, T., Mahmud, S. and Dachlan, T. (2002) 'Modelling The Deterioration of Bituminous Pavements In Indonesia Within A HDM-4 Framework', *Transport Research Laboratory (web search)*.

APPENDIX C

THE ROAD NETWORK ACCESSIBILITY INDEX (RNAI)

C.1 Definition

The Road Network Accessibility Index (RNAI) Accessibility in this research is defined as 'the extent to which road network infrastructure ease road users to reach their destination(s) throughout the year within a particular region' (Amrozi and Evdorides, 2019).

C.2 Goal and Objectives

Accessibility is used as a measurement tool to support regional development. The associated model emphasises how road infrastructure may be optimised to maintain accessibility and support regional development under changing climate conditions using the concept of equity.

The implementation of the accessibility model may have essential objectives:

1. To ensure equity or fairness both in the quality and distribution of accessibility for each person in the country. The concept of equity is chosen to maintain the accessibility level and minimise the disparity between locations to promote regional development.
2. To achieve sustainable road network accessibility, i.e. optimising the condition of road network assets to achieve an optimum level of accessibility under tight budget constraints and changing climate conditions.

C.3 Unit of Analysis

The focus of the RNAI measurement is the accessibility to all locations in need of transport services within an area (integral accessibility). It means that the unit of analysis represents a geographical area based on administrative, geospatial, or artificial boundaries, e.g. by province, island, village or district.

C.4 Components

The component of the RNAI model are shown in the folloing table.

The RNAI components and the link to the HDM-4 as a road appraisal tool

Component	Consideration of equity in the accessibility model			Link to HDM-4 software
	Requirement	Indicator	Quantification	
Network length (N)	Each region should have enough road network connections to reach all locations in need of transport services	Length of the road network within an area	Length of road network per land area (total road density)	Length of the road network
Condition (C)	Each region should have an adequate percentage of accessible road	A passable road which satisfies the minimum level of service, e.g., travel speed and riding comfort	Percentage or ratio of the road in a good or fair condition (based on predefined standards)	Roughness (IRI, m/km)
Pavement type (P)	Each region should have a satisfactory percentage of reliable road access (ensuring the road is always open throughout the year)	A*ll-weather* type of road pavement, i.e., road surface which may withstand climate exposure	Percentage or ratio of the sealed road surface, e.g., asphalt or concrete	Type of Pavement

C.5 Quantification

The RNAI model is callculated using the following formula:

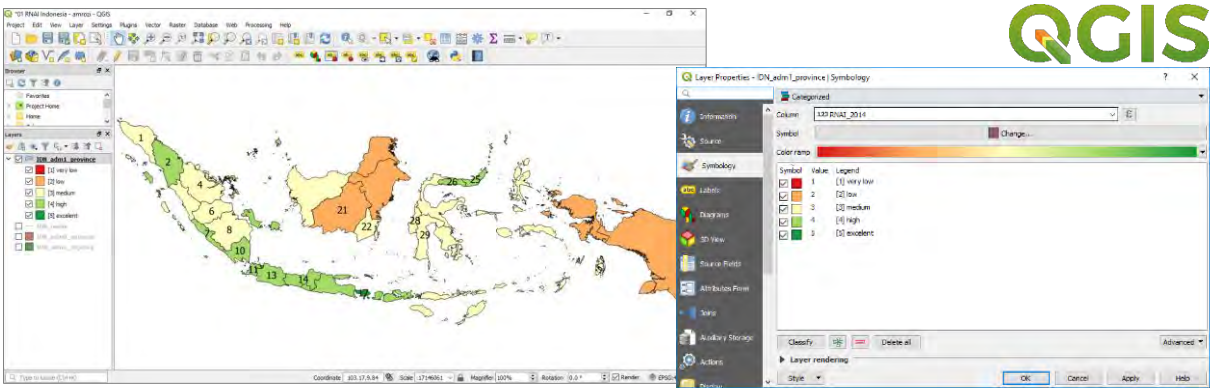
$$RNAI = \frac{1}{3} \times \left(min\left\{1, \frac{(L_{tn}/S)}{(L_{tn}/S)_{max}}\right\} + min\left\{1, \frac{(L_{gf}/S)}{(L_{gf}/S)_{max}}\right\} + min\left\{1, \frac{(L_{ac}/S)}{(L_{ac}/S)_{max}}\right\}\right)$$; range [0-1]

Where : $RNAI$ = The Road Network Accessibility Index ; L_{tn}= length of total road network; S = land area;L_{gf}= length of roads in good and fair condition; L_{ac}= length of sealed road surface (asphalt, cement).; $(L_{gf}/S)_{max}$= maximum value from the population, e.g. country or state.

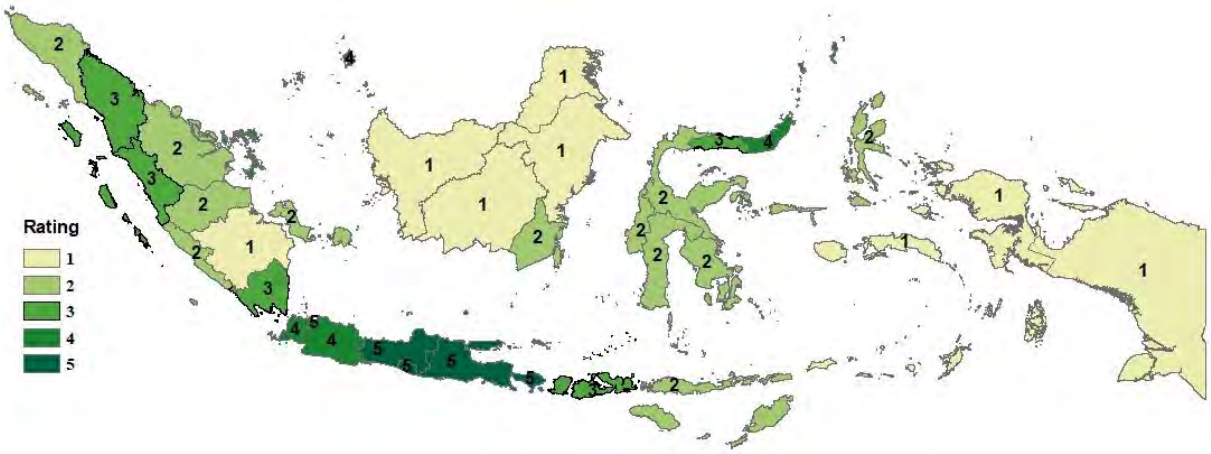
C.6 Presentation and visualisation of RNAI

The unit analysis of RNAI is a geographical area, either based on administrative, geospatial, or artificial boundaries. To present the dynamical value of RNAI between areas, besides using mathematical indices (index and star rating), a pictorial technique presentation such as graph and geospatial information system (map) can be added. A graphical presentation can be produced using Microsoft Excel. At the same time, an isochronal map can be generated using geographic information systems (GIS) software such as ArcGIS, MapInfo, Base, Geosoft, gisAMPS and QGIS. In this study, the isochronal map presentation does not require a complex GIS analysis. It only used to show the RNAI value. Software that is designed for developing countries, simple, and low-cost is preferable. Therefore, the QGIS software is favoured because it is free, user-friendly, and can be installed on Windows, Mac, Linux, BSD and Android. The QGIS software can be downloaded free of charge from the QGIS website, http://www.qgis.org. The procedure to present the isochronal map of RNAI value in QGIS is simple. The first step is preparing or creating a basic map of the case study area. The map can be drawn manually or imported using 'Map Composer' tool in QGIS and normally saved as a *shapefiles (.shp)*. Afterwards, the RNAI value should be inputted as an attribute in the map database through 'open attribute table' tool. The isochronal map is generated by showing that RNAI attribute value through 'symbology' option which located inside the layer properties of the map.

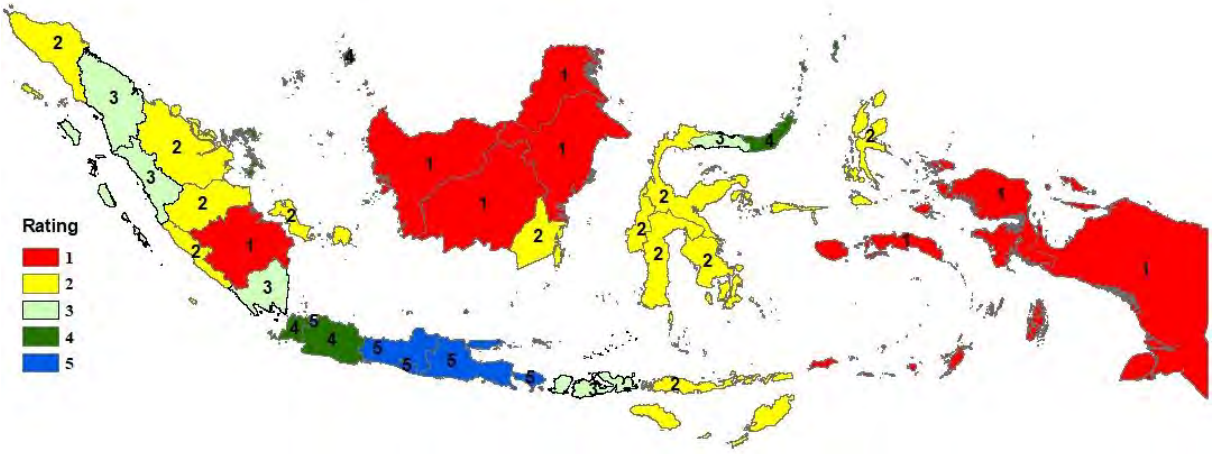
The step to visualise the isochronal vale of RNAI are as follows: change the symbol option into 'graduated' or 'categorized', choose the RNAI attribute which will be shown, choose the preferred colour ramp and set the required number of class, e.g. set into five different colours due to the five-star rating system. After clicking the 'OK' button, the isochronal map will be automatically generated.



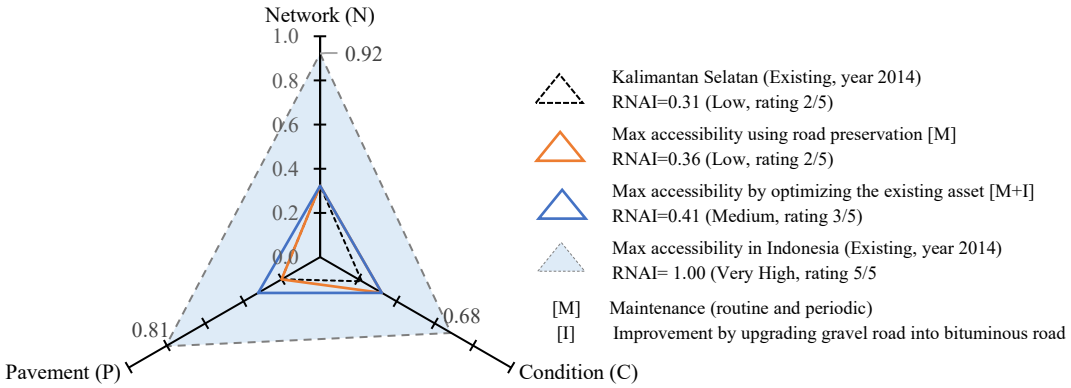
Interface of QGIS software



Isochronal Map Presentation



Isochronal Map Presentation



Radar chart to show the change in accessibility components

C.7 Interpretation of the RNAI Value

The outcome for the RNAI quantification is called an accessibility index. However, as the indexing scheme is hard for ordinary people to interpret the meaning, the index can be converted into a more straightforward measurement unit, such as a star rating. For creating the associated rating, the values are categorised into five equal scales known as the five-star rating system. A one-star rating represents the lowest level of accessibility, e.g. very remote or isolated, while a five-star rating represents the best accessibility.

Interpretation of the RNAI value

Accessibility (RNAI)			Meaning	
Index	Rating	Level		
> 0.8 – 1.0	5	Very High (excellent)	*Unrestricted access*	to a wide range of services and opportunities for social-economic interaction. The area has several route options. Road surfaces are mostly sealed and always reliable throughout the year.
>0.6 – 0.8	4	High (good)	*Relatively unrestricted access*	to a wide range of services and opportunities. The area has some route options. Road surfaces are mostly sealed and reliable throughout the year.
>0.4 – 0.6	3	Moderate (average)	*Some restrictions of access*	to a wide range of services and opportunities. The area has route options. Road surface is partly unsealed, but access is still reliable for vehicles throughout the year.
>0.2 – 0.4	2	Low (remote)	*Significantly restrictions of access*	to a wide range of services and opportunities. The area has limited route options. Road surface is partly unsealed and may not be reliable throughout the year.
0.0 – 2.0	1	Very Low (isolated)	*Very restricted access*	to reach services and opportunities. The area typically does not have different route options. Road surface is mostly unsealed and unreliable throughout the year.

C.8 Model limitation

The limitations that apply in the Road Network Accessibility Index (RNAI):

a. The developed accessibility model only focuses on road infrastructure and does not explicitly consider road traffic and land use component.
b. The RNAI assume that all activity centres in national, province and regency level (e.g. town centre, market, school, and hospital) has been connected by road network at least linked by one road.
c. The accessibility model (RNAI) was developed using Indonesia as the case study. However, the model may be adaptable for other countries after some adjustments

C.9 Innovative Features of the RNAI model

a. The RNAI model consider the concept of equity on the availability and condition of road infrastructure to promote regional social-economic development.
b. The RNAI integrate the concept of accessibility with climate change and road asset management.
c. The RNAI can be used as additional criteria in managing road asset and accessibility under changing climate conditions.
d. The RNAI is a simple model to link the communication between stakeholders in managing road network accessibility.

APPENDIX D

HIGHWAY DEVELOPMENT AND MANAGEMENT (HDM-4)

D.1 HDM-4 Inputs

H D M - 4

Road Sections – Basic

HIGHWAY DEVELOPMENT & MANAGEMENT

Study Name: 01 INDONESIA 2014 RNAI – IRMS [M]+[I] (upgrade gravel road)
Run Date: 05-12-2019

ID	Name	Speed Flow Type	Traffic Flow Pattern	Road Class	Climate Zone	Surface Class	Calibration Item	Length (Km)	Width (m)	Shoulder width (m)	ELanes
NAT1R1	A NAT1R1	Two Lane Standard	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Bituminous	Asphalt - Indonesia	231.00	7.00	2.00	2
NAT1R2	A NAT1R2	Two Lane Standard	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Bituminous	Asphalt - Indonesia	16.00	7.00	2.00	2
NAT2R1	A NAT2R1	Two Lane Standard	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Bituminous	Asphalt - Indonesia	531.00	7.00	2.00	2
NAT2R2	A NAT2R2	Two Lane Standard	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Bituminous	Asphalt - Indonesia	42.00	7.00	2.00	2
NAT2R3	A NAT2R3	Two Lane Standard	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Bituminous	Asphalt - Indonesia	10.00	7.00	2.00	2
NAT3R1	A NAT3R1	Two Lane Standard	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Bituminous	Asphalt - Indonesia	326.00	7.00	1.50	2
NAT3R2	A NAT3R2	Two Lane Standard	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Bituminous	Asphalt - Indonesia	24.00	7.00	1.50	2
NAT3R3	A NAT3R3	Two Lane Standard	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Bituminous	Asphalt - Indonesia	4.00	7.00	1.50	2
NAT3R4	A NAT3R4	Two Lane Standard	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Bituminous	Asphalt - Indonesia	3.00	7.00	1.50	2
NGT5R1	NGT5R1	Two Lane Road	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Unsealed	Gravel	12.00	6.00	1.50	2
NGT5R2	NGT5R2	Two Lane Road	MP Flow	[N] Primary or Trunk	RI-Base T27P200	Unsealed	Gravel	5.00	6.00	1.50	2
PAT1R1	A PAT1R1	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	28.00	7.00	1.50	2
PAT1R2	A PAT1R2	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	12.00	7.00	1.50	2
PAT1R3	A PAT1R3	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	15.00	7.00	1.50	2
PAT1R4	A PAT1R4	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	10.00	7.00	1.50	2
PAT2R1	A PAT2R1	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	184.00	7.00	1.50	2
PAT2R2	A PAT2R2	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	96.00	7.00	1.50	2
PAT2R3	A PAT2R3	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	24.00	7.00	1.50	2
PAT2R4	A PAT2R4	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	14.00	7.00	1.50	2
PAT3R1	A PAT3R1	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	146.00	7.00	1.50	2
PAT3R2	A PAT3R2	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	61.00	7.00	1.50	2

ID	Name	Speed Flow Type	Traffic Flow Pattern	Road Class	Climate Zone	Surface Class	Calibration Item	Length (Km)	Width (m)	Shoulder width (m)	ELanes
PAT3R3	A PAT3R3	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	55.00	7.00	1.50	2
PAT3R4	A PAT3R4	Two Lane Standard	MP Flow	[P] Secondary or Main	RI-Base T27P200	Bituminous	Asphalt - Indonesia	56.00	7.00	1.50	2
PGT5R1	PGT5R1	Two Lane Road	MP Flow	[P] Secondary or Main	RI-Base T27P200	Unsealed	Gravel	52.00	6.00	1.50	2
PGT5R2	PGT5R2	Two Lane Road	MP Flow	[P] Secondary or Main	RI-Base T27P200	Unsealed	Gravel	33.00	6.00	1.50	2
PGT5R3	PGT5R3	Two Lane Road	MP Flow	[P] Secondary or Main	RI-Base T27P200	Unsealed	Gravel	22.00	6.00	1.50	2
PGT6R1	PGT6R1	Two Lane Road	MP Flow	[P] Secondary or Main	RI-Base T27P200	Unsealed	Gravel	35.00	6.00	1.50	2
PGT6R2	PGT6R2	Two Lane Road	MP Flow	[P] Secondary or Main	RI-Base T27P200	Unsealed	Gravel	6.00	6.00	1.50	2
PGT6R3	PGT6R3	Two Lane Road	MP Flow	[P] Secondary or Main	RI-Base T27P200	Unsealed	Gravel	3.00	6.00	1.50	2
RAT1R1	A RAT1R1	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	494.00	7.00	1.00	2
RAT1R2	A RAT1R2	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	387.00	7.00	1.00	2
RAT1R3	A RAT1R3	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	53.00	7.00	1.00	2
RAT1R4	A RAT1R4	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	24.00	7.00	1.00	2
RAT2R1	A RAT2R1	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	675.00	7.00	1.00	2
RAT2R2	A RAT2R2	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	519.00	7.00	1.00	2
RAT2R3	A RAT2R3	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	984.00	7.00	1.00	2
RAT2R4	A RAT2R4	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	874.00	7.00	1.00	2
RAT3R1	A RAT3R1	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	462.00	7.00	1.00	2
RAT3R2	A RAT3R2	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	223.00	7.00	1.00	2
RAT3R3	A RAT3R3	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	753.00	7.00	1.00	2
RAT3R4	A RAT3R4	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Bituminous	Asphalt - Indonesia	433.00	7.00	1.00	2
RGT5R1	RGT5R1	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Unsealed	Gravel	1,470.00	6.00	1.00	2
RGT5R2	RGT5R2	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Unsealed	Gravel	651.00	6.00	1.00	2
RGT5R3	RGT5R3	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Unsealed	Gravel	154.00	6.00	1.00	2
RGT5R4	RGT5R4	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Unsealed	Gravel	122.00	6.00	1.00	2
RGT6R1	RGT6R1	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Unsealed	Gravel	1,092.00	6.00	1.00	2
RGT6R2	RGT6R2	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Unsealed	Gravel	656.00	6.00	1.00	2
RGT6R3	RGT6R3	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Unsealed	Gravel	187.00	6.00	1.00	2
RGT6R4	RGT6R4	Two Lane Road	Commuter	[R] Tertiary or Local	RI-Base T27P200	Unsealed	Gravel	249.00	6.00	1.00	2

H D M - 4

Vehicle Fleet - Basic

HIGHWAY DEVELOPMENT & MANAGEMENT

Study Name: 01 INDONESIA 2014 RNAI – IRMS [M]+[I] (upgrade gravel road)
Run Date: 05-12-2019

Motorised Vehicle Types:

Name	Base Type	PCSE	No. of Wheels	No. of Axles	Tyre Type	Tyre Base Recaps	Tyre Retread Cost (%)	Annual Km	Annual Work Hours	Avg Life	Private Use (%)	Pass-engers	Work Related Trips (%)	ESALF	Oper. Weight (t)
01 Motorcycle	Motorcycle	0.50	2	2	Bias ply	1.30	15.0	16,000	1,300	10	100	2.0	50.0	0.0	0.3
02 Car	Medium Car	1.00	4	2	Radial ply	1.30	15.0	20,000	1,300	10	100	4.0	60.0	0.0	1.2
03 Utility - passenger	Mini Bus	1.00	4	2	Radial ply	1.30	15.0	16,000	1,300	10	50	6.0	60.0	0.0	1.5
04 Utility - freight	Light Truck	1.30	4	2	Bias ply	1.30	15.0	34,000	1,300	10	50	2.0	50.0	0.0	1.5
05 Small bus	Mini Bus	1.30	4	2	Radial ply	1.30	15.0	72,000	2,400	10	0	20.0	65.0	0.2	5.3
06 Large bus	Heavy Bus	1.50	6	2	Bias ply	1.30	15.0	100,000	2,400	10	0	40.0	40.0	1.5	13.5
07 2-axle truck - light	Light Truck	1.30	6	2	Bias ply	1.30	15.0	60,000	2,000	10	0	2.0	50.0	1.0	13.5
08 2-axle truck - medium	Medium Truck	1.50	10	3	Bias ply	1.30	15.0	85,000	2,300	10	0	2.0	50.0	3.0	16.2
09 3-axle truck - heavy	Heavy Truck	1.80	12	4	Bias ply	3.39	60.0	80,000	2,200	10	0	2.0	50.0	4.0	21.0
10 Truck articulated + trailer	Articulated Truck	2.20	16	5	Bias ply	4.57	60.0	100,000	2,000	10	0	2.0	0.0	4.6	36.0
11 Tractor + semitrailer	Articulated Truck	2.20	14	4	Bias ply	1.30	15.0	77,000	2,100	10	0	2.0	50.0	5.0	30.0

Non-Motorised Vehicle Types:

Name	Base Type	Wheel Type	No. of Wheels	Wheel Diameter (m)	Op. Weight (kg)	Payload (kg)	Avg Life	Work Hours	Annual Km	Passengers
12 Cycle	Bicycle	Pneumatic	2	0.70	100	35	10	150	2,500	1.00

H D M - 4

Vehicle Fleet - Basic

HIGHWAY DEVELOPMENT & MANAGEMENT

Study Name: 01 INDONESIA 2014 RNAI – IRMS [M]+[I] (upgrade gravel road)
Run Date: 05-12-2019

Currency: Thousand Indonesian Rupiah

Motorised Vehicle Types:

Name	Base Type	New Vehicle	Replace Tyre	Fuel (per litre)	Lubr. Oil (per litre)	Maint Labour (per hr)	Crew Wages (per hr)	Annual Interest (%)	Passenger Work Time (per hr)	Passenger Non-Work (per hr)	Cargo Holding (per hr)
01 Motorcycle	Motorcycle	17,000	160	10.00	31.00	21.40	0.00	7.00	21.40	12.10	0.00
02 Car	Medium Car	210,000	500	10.00	40.00	21.40	12.90	7.00	21.40	5.00	0.00
03 Utility - passenger	Mini Bus	634,000	3,800	24.30	68.50	21.40	12.90	7.00	21.40	3.20	0.00
04 Utility - freight	Light Truck	400,000	900	10.00	40.00	21.40	12.10	7.00	21.40	5.00	2.46
05 Small bus	Mini Bus	400,000	2,500	10.00	40.00	21.40	12.10	7.00	21.40	5.00	0.00
06 Large bus	Heavy Bus	600,000	3,500	10.00	40.00	21.40	12.10	7.00	21.40	5.00	0.00
07 2-axle truck - light	Light Truck	220,000	2,500	10.00	40.00	21.40	12.10	7.00	21.40	5.00	2.46
08 2-axle truck - medium	Medium Truck	250,000	3,500	10.00	40.00	21.40	12.10	7.00	21.40	5.00	7.38
09 3-axle truck - heavy	Heavy Truck	700,000	3,500	10.00	40.00	21.40	12.10	7.00	21.40	5.00	11.07
10 Truck articulated + trailer	Articulated Truck	1,000,000	35,000	10.00	40.00	21.40	12.10	7.00	21.40	5.00	13.94
11 Tractor + semitrailer	Articulated Truck	1,000,000	3,500	10.00	40.00	21.40	12.10	7.00	21.40	5.00	13.94

Non-Motorised Vehicle Types:

Name	Base Type	Purchase Cost	Crew Wages (per hr)	Passenger Time (per hr)	Cargo Holding (per hr)	Energy Used (per MJ)	Annual Interest (%)
12 Cycle	Bicycle	4,000	0.00	14.00	0.00	0.00	7.00

D.2 HDM-4 Outputs

D.2.1 Road condition based on accessibility management scenario in Chapter 8

Roughness based on accessbility management scenario in Chapter 8 (IRI, m/km)

Year		1	2	3	4	5	6	7	8
		Do Nothing	Do Minimum	IRMS [M]	IRMS [M+I]	IRMS [M+I+D]	IRMS [M+I+D]	IRMS [M+I+D]	IRMS [M+I+D]
2014	0	7.97	7.97	7.97	7.97	7.97	7.97	7.97	7.97
2015	1	10.69	10.64	10.19	10.19	10.19	10.19	10.19	10.19
2016	2	12.80	11.36	8.42	3.39	3.24	3.19	3.24	3.19
2017	3	13.48	11.90	8.13	3.07	6.55	7.93	3.08	3.09
2018	4	13.88	10.79	8.04	2.95	7.47	9.27	3.10	3.16
2019	5	14.21	10.99	8.10	3.00	7.63	9.47	3.23	3.32
2020	6	14.57	11.17	4.85	3.13	7.78	9.62	2.83	2.71
2021	7	14.94	7.16	6.72	2.64	7.53	9.47	2.58	2.56
2022	8	15.28	9.78	7.87	2.78	4.33	4.94	2.74	2.72
2023	9	15.62	11.11	8.24	2.93	6.05	7.29	2.90	2.89
2024	10	16.04	11.48	8.09	2.74	7.12	8.86	2.86	2.91
2025	11	16.54	11.08	4.86	2.50	7.31	9.22	2.79	2.91
2026	12	17.05	11.16	6.97	2.61	7.47	9.39	2.95	3.09
2027	13	17.45	11.25	8.00	2.74	4.53	5.23	2.52	2.43
2028	14	17.70	11.51	8.30	2.88	6.44	7.85	2.66	2.58
2029	15	17.89	11.81	8.47	3.03	7.68	9.53	2.82	2.74
2030	16	18.05	11.64	5.66	3.14	8.00	9.92	2.95	2.88
2031	17	18.16	8.08	7.56	2.97	7.96	9.94	2.92	2.90
2032	18	18.21	10.40	8.24	2.90	4.89	5.68	2.95	2.97
2033	19	18.26	10.76	8.38	2.93	6.90	8.48	3.05	3.10
2034	20	18.28	10.65	8.47	2.77	7.82	9.83	3.04	3.15

Where : [5] add 60% garvel road, [6] add 110% garvel road, ([7] add 60% asphalt road, [add] add 110% asphalt road

D.2.2 Accessibility and road condition under contrained budget scenario in Chapter 8

UNDER CONSTRAINED BUDGET

Year		RNAI						Roughness					
		F1	F2	F3	A1	A2	A3	F1	F2	F3	A1	A2	A3
2014	0	0.31	0.31	0.31	0.31	0.31	0.31	7.97	7.97	7.97	7.97	7.97	7.97
2015	1	0.34	0.34	0.32	0.32	0.28	0.28	6.65	7.22	7.89	8.78	9.61	9.89
2016	2	0.41	0.39	0.37	0.33	0.30	0.29	3.25	4.47	6.08	8.31	9.78	10.88
2017	3	0.41	0.39	0.37	0.33	0.30	0.29	3.01	4.34	6.26	8.65	10.04	11.23
2018	4	0.41	0.39	0.36	0.32	0.30	0.28	2.98	4.29	6.39	8.83	10.18	11.34
2019	5	0.41	0.39	0.35	0.32	0.30	0.27	3.06	4.37	6.67	9.11	10.44	11.54
2020	6	0.41	0.39	0.35	0.32	0.30	0.27	2.89	4.25	6.74	9.26	10.64	11.74
2021	7	0.41	0.39	0.35	0.34	0.33	0.32	2.71	4.13	6.76	7.66	8.39	8.45
2022	8	0.41	0.39	0.35	0.32	0.30	0.27	2.85	4.27	6.93	8.65	9.95	10.56
2023	9	0.41	0.39	0.35	0.32	0.30	0.27	2.84	4.25	7.07	9.28	10.65	11.68
2024	10	0.41	0.39	0.35	0.32	0.30	0.27	2.62	4.02	7.10	9.38	10.73	11.92
2025	11	0.41	0.39	0.35	0.32	0.30	0.27	2.55	3.95	7.11	9.41	10.67	11.92
2026	12	0.41	0.39	0.35	0.32	0.30	0.27	2.68	4.06	7.18	9.48	10.74	11.99
2027	13	0.41	0.39	0.35	0.32	0.30	0.27	2.81	4.19	7.26	9.56	10.82	12.06
2028	14	0.41	0.39	0.35	0.32	0.30	0.27	2.95	4.32	7.35	9.64	10.89	12.14
2029	15	0.41	0.39	0.35	0.32	0.30	0.27	3.08	4.44	7.43	9.70	10.96	12.20
2030	16	0.41	0.39	0.35	0.32	0.30	0.27	3.06	4.41	7.46	9.74	10.96	12.19
2031	17	0.41	0.39	0.35	0.34	0.31	0.30	2.93	4.27	7.45	8.30	9.04	9.39
2032	18	0.41	0.39	0.35	0.32	0.30	0.27	2.91	4.24	7.41	9.17	10.42	11.35
2033	19	0.41	0.39	0.35	0.32	0.30	0.27	2.85	4.19	7.32	9.55	10.72	11.98
2034	20	0.41	0.39	0.35	0.32	0.30	0.27	2.84	4.18	7.28	8.89	10.74	12.14

D.2.3 Accessbility and road condition based on extreme weather scenario in Chapter 8

Degradation due to extreme weather

RNAI						Roughness					
[3]	[4]	[5]	[6]	[7]	[8]	[3]	[4]	[5]	[6]	[7]	[8]
0.31	0.31	0.31	0.31	0.31	0.31	7.97	7.97	7.97	7.97	7.97	7.97
0.26	0.26	0.25	0.26	0.26	0.26	10.16	10.33	10.69	10.34	10.19	10.69
0.30	0.31	0.30	0.32	0.30	0.26	8.42	7.98	8.45	7.01	8.42	12.80
0.30	0.30	0.30	0.31	0.30	0.26	8.13	7.89	8.15	6.96	8.13	13.48
0.30	0.30	0.30	0.31	0.30	0.25	8.04	7.95	8.12	6.99	8.04	13.88
0.30	0.30	0.30	0.31	0.30	0.24	8.10	8.05	8.18	7.07	8.10	14.21
0.36	0.35	0.36	0.35	0.36	0.24	4.85	5.25	4.92	4.88	4.85	14.57
0.33	0.33	0.33	0.34	0.33	0.24	6.72	6.49	6.73	5.61	6.72	14.94
0.30	0.30	0.30	0.31	0.30	0.24	7.87	7.73	7.87	6.77	7.87	15.28
0.30	0.30	0.30	0.31	0.30	0.24	8.24	8.21	8.23	7.21	8.24	15.62
0.30	0.30	0.30	0.31	0.30	0.22	8.09	8.08	8.07	7.07	8.09	16.04
0.36	0.35	0.36	0.35	0.36	0.21	4.86	5.26	4.90	4.74	4.86	16.54
0.30	0.31	0.30	0.32	0.30	0.21	6.97	6.72	7.01	5.80	6.97	17.05
0.30	0.30	0.30	0.31	0.30	0.20	8.00	7.88	8.04	6.90	8.00	17.45
0.30	0.30	0.30	0.31	0.30	0.20	8.30	8.28	8.34	7.26	8.30	17.70
0.30	0.30	0.30	0.31	0.30	0.20	8.47	8.47	8.51	7.44	8.47	17.89
0.36	0.35	0.36	0.35	0.36	0.20	5.66	6.06	5.69	5.49	5.66	18.05
0.30	0.31	0.30	0.32	0.30	0.20	7.56	7.29	7.58	6.35	7.56	18.16
0.30	0.30	0.30	0.31	0.30	0.20	8.24	8.13	8.26	7.15	8.24	18.21
0.30	0.30	0.30	0.31	0.30	0.20	8.38	8.36	8.46	7.33	8.38	18.26
0.30	0.30	0.30	0.31	0.30	0.20	8.47	8.47	8.55	7.43	8.47	18.28

APPENDIX E

PUBLICATION

E.1 The 7th International Conference on Bituminous Mixtures and Pavements [7th ICONFBMP], Thessaloniki, Greece, 12-14 June 2019

E.1.1 Paper manuscript

Economic Optimisation of Road Network Accessibility

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ABSTRACT: An appropriate road network management system should aim at achieving a minimum level of accessibility to all locations in need of transport services. Failure to maintain accessibility across the regions of a country, hampers economic and social development. There are several accessibility models that may be used to examine the road networks' accessibility levels, but most of them do not consider directly the condition of the road infrastructure and its economic life. There is a need therefore for an enhanced accessibility model to address it. This paper presents a methodology and show how a new accessibility index methodology may be defined and linked with an economic analysis tool (i.e. HDM4) with the view to develop sustainable maintenance and development plans for the road networks' infrastructure. The result proves that the condition of road network may be optimised under budget constraints to achieve a level of accessibility that promotes economic development.

1 INTRODUCTION

Accessibility has a significant influence in regional development (Banister & Berechman 2003). Failure to maintain accessibility across the regions of a country hampers economic and social development. A higher level of accessibility offers more opportunity for people to do interaction and perform social activities in any location within a regional area, e.g. province or regency. As a result, it influences the regional development which, for instance, reflected by Gross Domestic Product (GDP) per capita (Fig. 1).

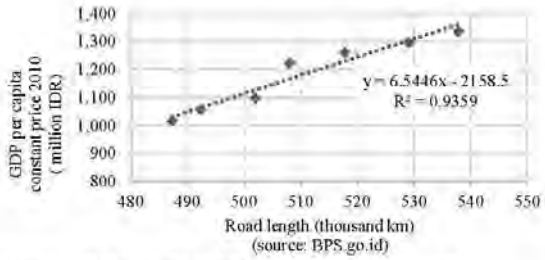


Figure 1. Road asset Vs GDP per capita in Indonesia.

In developing countries, such as Indonesia, accessibility is varying with a significant disparity between areas. However, it is believed that increasing accessibility within a location/area is an initial step to reverse the vicious cycle of poverty and urbanisation, the movement of people from rural areas to urban areas to find a better job or other social-economic activities. In Jakarta, a market may be achieved by less than 2 minutes walking distance, but in Papua, it may take half a day to reach the nearest market. That makes the most population of Indonesia want to move to Jakarta due to this massive magnet for social-economic opportunities. Meanwhile, their hometown still has restricted access or even isolated. In the national context, the disparity of accessibility increases social sentiment between regions and potentially threaten national unity, especially for border area between countries. Therefore, the accessibility level needs to be improved, and the gap between areas must be minimized.

The concept of accessibility has been widely used for transport and land-use planning. Accessibility is a simple term that easy to be accepted by everyone. In these cases, accessibility becomes an effective tool to bridge the communication between the engineer, road user, and politician mainly to promote and increase the budget allocation for road infrastructure management and development.

An appropriate road network management system should aim at achieving a minimum level of accessibility to all locations in need of transport services. There are several accessibility models that may be used to examine the road networks' accessibility levels, but most of them do not directly consider the condition of the road infrastructure and its economic life. There is a need therefore for an enhanced accessibility model which coupled with life cycle analysis

of road assets may offer a definition of sustainable standards and strategies that will enable a minimum level of accessibility.

2 ACCESSIBILITY

2.1 *Definition of accessibility*

Accessibility leads to different meaning depending on the approach and context. Based on previous studies (Hansen 1959, Ingram 1971, Dalvi & Martin 1976, Burns 1979, Ben-Akiva & Lerman 1979, U.S. Department of the Environment 1996, Odoki et al. 2000, Berdica 2002, Geurs & Wee 2004), the accessibility concept is generally defined as the "ease of reaching destinations". The world 'ease' is an individual's preference that may influence many factors and perspectives. This implies that accessibility will indisputably have many interpretations and methods of measurement.

A good level of accessibility in a regional area may be achieved by a proper land-use and transportation system. By considering an infrastructure-based accessibility approach, Berdica (2002) defined accessibility as "the serviceability of a link/route/road network which describes the possibility to use that link/route/road network during a given period." Meanwhile, a wider understanding comes from Geurs & Wee (2004) that defined accessibility as "the extent to which land-use and transport systems enable (groups of) individuals to reach activities or destinations by means of a (combination of) transport mode(s)". Although the definition from Geurs & Wee seems to consider two aspects, in the application it focuses more on land-use than on the transportation component.

In this study, the concept of accessibility focusses on how road networks infrastructure can be economically optimised to support regional development and linked to extreme weather condition. Thus, accessibility measurement will be named as Road Network Accessibility Index (RNAI). RNAI is defined as the extent to which road networks infrastructure can ease road users to reach their destination(s) within a regional area during the whole year period. It means that RNAI stresses how road network infrastructure features can support the accessibility within an area by its condition and its available asset. The concept of RNAI focuses on equity by considering the availability, robustness, and quality of road infrastructures to give road users more opportunity and option with a lower travel cost to reach their destination(s) within a regional area.

2.2 *Accessibility measurement*

In general, accessibility typically considers 'opportunity activities at destination' and 'travel impedance'. High level of accessibility is achieved when there are more travel options (route, mode) and the lower travel impedance (distance, time, costs, and effort) to reach possible destinations.

Improving accessibility can be generated from various accessibility-enhancing strategies. The variety of approach and consideration makes measuring accessibility is not as simple as imagined, yet it is complicated. It is because the term "to ease" in the accessibility definition follows individuals' perception which related to many factors. Various types and point of views to measure accessibility are classified in Table 1.

2.3 *Best Practice in developing countries*

In this research, accessibility is used to measure road networks and land-use performance, especially in developing countries. Based on literature review, there are some accessibility measurements which may appropriate to measure it, i.e. Integrated Rural Accessibility Planning (IRAP), The Accessibility/ Remoteness Index of Australia (ARIA), Rural Access Index (RAI), and road density (Donnges 2003, Department of Health Australia 2011, Roberts et al. 2006).

2.3.1 Integrated Rural Accessibility Planning

Integrated Rural Accessibility Planning (IRAP) is developed by the International Labor Organization (ILO), as a part of strategies to overcome poverty in developing countries. IRAP is defined as the level of

Table 1. Accessibility types and measurements

Dimension	Type of measurement	Example of quantification
Perspective *(Geurs & Eck 2001, Odoki et al. 2001, Pirie 1979)*	a. infrastructure-based: performance or service level b. location-based: spatially distributed activities c. person-based: individual level d. utility-based: benefits derived from access to distributed activity	a. level of congestion, average travel speed b. number of jobs within 30 minutes away c. number of possible activities in which an individual can participate at a given time d. economic and/or financial benefit
Connectivity relationship *(Ingram 1971, Neft 1966)*	a. relative accessibility: between two places (or points) b. integral accessibility: interconnection a place (or point) with any places (or points) within an area	a. relative: $a\text{-}xy = (a_{xy}+a_{yx})/2$ b. integral: $A_i = \sum a_{ij}$
Presentation method *(Cohen & Basner 1972)*	a. mathematical indices - accessibility index b. pictorial technique	a. index: $A_{ij} = f(a_j, t_{ij})$ b. pictorial: graphs, isochronal maps

ease to reach services of basic need from rural household such as access to water, firewood, employment, health service, education and markets (Dissel 2003).

ILO has extensive research and broad coverage of IRAP implementation. Using a decentralised development process approach, IRAP promotes community participatory and optimum use of local resources such as labour (Donnges 2003). In the assessment, the IRAP interventions do not only focus on the physical infrastructure, e.g. construction roads or bridges, but also covering land-use planning, transportation mode, and quality of services. In general, IRAP is measured by taking into account the number of populations with travel time as the weighting opportunity.

2.3.2 The Accessibility/Remoteness Index of Australia (ARIA)

Accessibility/Remoteness Index of Australia (ARIA) is a topographical accessibility index that reflects the ease of people to reach (or to access) services in a non-metropolitan area based on road distances (Department of Health Australia 2011). The closest the location to a big town or capital city the better accessibility perceived. ARIA believes that bigger town/capital city can supply all people's need both for social or economic activities.

ARIA measures remoteness of access by calculating the road distance needed to reach 4-6 nearest categories of the service centre. In practice, the service centre in ARIA is defined as Urban Centers with a population of 5,000 or more with General Post Office (GPO) as the central point, known as km zero, for the distance measurement.

ARIA score ranging from 0 to 12 with the maximum score for each category is 3. Zero score of ARIA indicates that the location has the highest level of access to services. Meanwhile, the maximum score (ARIA=12) indicates the location has the lowest level of access to services. Recently, there are three variances of ARIA measurement known as ARIA, ARIA^{+} and ARIA^{++}. The difference between them is the number of service centre categories which result in a different range of index scale (see Table 2).

2.3.3 Rural Access Index (RAI)

Rural Access Index (RAI) is developed by Roberts et al. (2006) under sponsorship from World Bank to assess the critical role of access and mobility in term of poverty and isolation reduction in developing countries. RAI utilise cumulative accessibility measure approach. It measures the proportion of people who live within two kilometres distance away from the all-season road. All-season road refers to a road that can be used all year round by any rural transportation mode such as pick-up truck, bicycle, and horse-drawn carriage (Roberts et al. 2006, World Bank Group 2016). The essence of 'all season' road is not lies on the pavement type, but it is dealing more with the road condition and its performance. For instance, paved road with high roughness become inaccessible during rainy season due to severer damage.

Table 2. Service centre category of ARIA index

Service centre category	Number of populations (persons)		
	ARIA	ARIA^{+}	*ARIA^{++}
A	≥ 250,000		
B	48,000 – 249,999		
C	5,000 – 17,999		
D	5,000 – 17,000		
E	n/a	1,000 - 4,999	
*F	n/a	n/a	200 – 999
Range of index	0 – 12	0 – 15	0 - 20

*only applicable/used in a very remote area;

2.3.4 Road density

Road density is used as world development indicators by the world bank. Road density defined as the total length of the road network ratio to regions' land area. The higher road density, the higher option and connection for an individual to travel within the area.

3 METHODOLOGY

3.1 *Approach*

Accessibility may be described by many factors leading to a different unit of measurement. To address this, the RNAI model is developed using a composite indicator model. After the RNAI is developed, the RNAI parameter is used to adjust HDM-4 input such as the number of road asset, the pavement type, pavement strength and road condition which is measured by roughness and surface distress. The lifecycle cost analyses in HDM-4 will be used to find the budget to reach a minimum level of accessibility, e.g. moderate level of accessibility.

3.2 *Composite indicators model of RNAI*

The Road Network Accessibility Index (RNAI), is developed using composite indicators and statistical analysis following "Handbook on Constructing Composite Indicators" developed by (OECD 2008). In general, the development of the RNAI model follows the procedure in Figure 2.

After the model form is formed, sensitivity analysis is conducted to capture the effect and influence of changing in input variables on the output of the developed RNAI model. In addition, linking RNAI as a road infrastructure-based accessibility index to

another accessibility indicator is also important. Although both indexes are measuring accessibility, they have a different scoring mechanism. In this case, RNAI is compared with existing accessibility indices and evaluated using statistical analyses to verify the RNAI model is suitable to describe the road network accessibility level within a regional area.

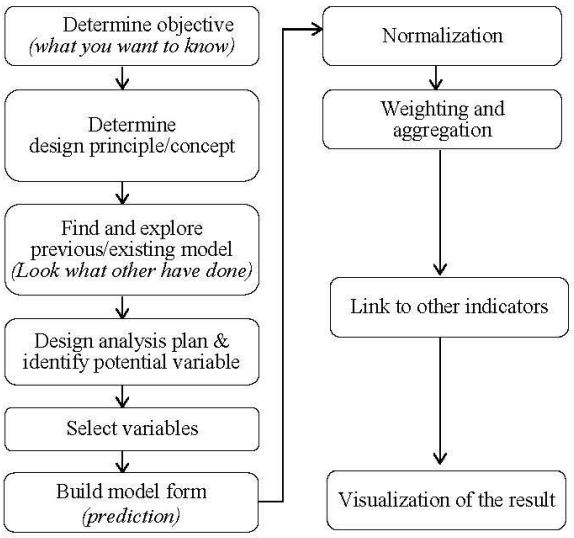


Figure 2. RNAI model development.

3.3 *HDM-4 lifecycle-cost analysis*

Road maintenance has a purpose to reduce pavement deterioration rate (lowering vehicle operation cost) and to preserve accessibility by keeping road networks always open (Robinson 2008). The choice of roadwork maintenance not only should satisfy engineering requirement but also should be economically adjusted using Life-Cycle Cost Analysis (LCCA).

In this research, proposed standards and strategies are evaluated economically using HDM-4, a standard decision support tool in road asset management, intended for strategic level of analysis. In this level of analysis, HDM-4 can calculate budget requirements based on predefined maintenance standards and strategies. Apart from that, if the budget is limited, it can simulate the optimal road network performance based on the budget constraint (Kerali et al. 2000). As outputs, simulated road asset condition such as roughness and another road asset attribute such as total length of road asset and type of surface payment can be used to re-calculate Road Network Accessibility Index (RNAI). This re-calculation is important to make sure the simulated result has satisfied the predefined target of accessibility level.

4 MODEL DEVELOPMENT: RNAI

4.1 Objective and approach

Accessibility is an important sustainable development indicator. It is believed that applying accessibility measurement will be beneficial for local planning and promote project-based coordination among different public agencies (El-Geneidy et al. 2011). In general, accessibility is essentially talking about the quality of locations to reach various meaningful destinations, e.g. work, school, hospital, shopping and other services (McCahill & Ebeling 2015). However, each accessibility measurement has its own specific goal and approach to address the accessibility problem.

Several accessibility models may be used to examine road networks' accessibility levels, but most of them do not directly consider the condition of the road infrastructure and its economic life. In this study, Road Network Accessibility Index (RNAI) is developed as an accessibility measurement which focuses on road infrastructure and its economic life to support regional development. RNAI defines the extent to which road network infrastructure and condition can ease road users to reach their destinations within a regional area during the whole year period. The scope is accessibility to all locations in need of transport services within an area. To achieve this, the approach is as follows: First, a higher level of road network accessibility should not only be dictated by the number of km road invested (road network) within an area but also determined by the condition and the reliability of the road performance itself. The more km length of road network invested in a geographical area the better. However, if the road surface mostly in 'poor' or 'bad' condition, as a consequence the road becomes not reliable or even un-accessible, e.g. the road cannot provide a minimum standard of road service/performance or road may be blocked during the rainy season due to worsening road condition. Therefore, at the operational level, road network with a poor/bad road condition must be reflected and indicated by a lower accessibility index.

Second, high levels of accessibility disparity between regions need to be minimised using the equity concept. In the context of the RNAI, this may be achieved by setting a standard for a minimum level of accessibility. Variances in accessibility levels are inevitable. This may be well accepted if the gap/disparity is not significant and the accessibility condition meets the minimum standard of national accessibility index. The equity consideration used in RNAI are: 1) Each area should have equal road network connection to reach all locations in need of transport services; 2) Each road network (RN)

should have an equal percentage of accessible road which satisfies standards of travel speed and comfort; 3) Each road network should have equal percentages of all-weather road, i.e. a reliable road which always open (in service) throughout the year.

Third, to bridge communication between road authorities and other stakeholders (e.g. government, road user, and road board member), the index should be related with a road infrastructure-based parameter which in turn can be linked with HDM-4. In addition, to anticipate political spoil, the measurement needs to be more quantitative rather than qualitative.

4.2 Parameter

In road asset management, there are many technical indicators. Based on the objective and approach of the RNAI, the measurement component should consider three significant parameters from road asset management which may be linked with HDM-4, i.e. availability of road asset (A_{rd}); condition of road asset (C_{gf}); and pavement type of road surface (P_{ac}). The index is intended to be implemented in developing countries which has a limited budget, resources, and technology. Thus, the selection criteria to choose and build the RNAI parameters are: 1) Measurement should focus on road infrastructure; 2) Data should be available to the public (promote public awareness); 3) Data collection should be cheap and easy; 4) Simple calculation; 5) The value of RNAI should be easy to be interpreted. Consideration of RNAI Parameters and the link to HDM-4 can be seen in Table 3.

4.3 Model form

The basic quantification form of RNAI are:

$$RNAI = f(A_{rd}, C_{gf}, P_{ac}) \quad (1)$$

$$RNAI = A_{rd} + C_{gf} + P_{ac} \quad (2)$$

$$A_{rd} = \frac{total\ road\ km}{square\ km\ of\ land\ area}\ \frac{[km]}{[km^2]}$$

$$C_{gf} = \frac{length\ of\ steady\ (good + fair)\ road\ condition}{total\ road\ length}\ \frac{[km]}{[km]}$$

$$P_{ac} = \frac{length\ of\ sealed\ road\ surface\ (asphalt + cement)}{total\ road\ length}\ \frac{[km]}{[km]}$$

where $RNAI$ = Road Network Accessibility Index; A_{rd} = availability of road asset; C_{gf} = condition of road asset; and P_{ac} = pavement type of road surface.

4.4 Normalisation

Normalisation has an objective to bring all parameters into the same unit. In the RNAI development index, the selected method is categorical scale. This method satisfies the theoretical concept and is widely used also because it is flexible and easy to understand (OECD 2008).

4.5 Weighting and aggregation

Weighting parameters reflect how important and significant the influence of each parameter to the index outcome is. Since the RNAI focus on the equity concept, the selected weighting method to be used is the equal weight method. Equal weight is a simple method which is not affected by an outlier. In this paper, the RNAI is developed using Indonesia as a study case. A definition of the RNAI star rating is given in Table 4 together with the total scores associated with the sum of the scores for each of its components (see Table 5).

4.6 Presentation and visualisation

Based on Indonesia asset database (see Figure 3), most of the accessibility levels are in moderate condition (43%). Based on provincial area, Jakarta and Bali are the most accessible location in Indonesia (RNAI=13, star rating 5) meanwhile Papua is the most remote area (RNAI=8, star rating 3). The overall RNAI score in Indonesia can be seen in Table 6.

Table 3. Consideration of RNAI parameters and the link to HDM-4

Component	Equity consideration		Quantification	Goal*	Link to HDM-4
	Requirement	Parameter			
Availability (A_{rd})	Each area should have a fair and equal road network connection	Invested road asset within an area (road density)	Km of road per sq. km of land area	D	number of road asset
Condition (C_{gf})	Each road network should have an equal percentage of accessible road	Passable road which satisfy travel speed and riding comfort	Percentage of road with good or fair condition	P	roughness (IRI), surface distress
Pavement (P_{ac})	Each road network should have an equal percentage of reliable road access (assuring road is always open whole year period)	All-weather/all season type of road pavement	Percentage of sealed road surface	D/P	pavement type, pavement strength

*D=Development; P=Preservation

Table 4. RNAI score and meaning

RNAI			Meaning
∑ Score	Star rating	Level	
13 - 15	5	Very high (excellent)	*Unrestricted access* to wide range of services and opportunities for social-economic interaction. The area has some route option with a reliable sealed road during the whole year period.
10 - 12	4	High	*Relatively unrestricted access* to a wide range of services and opportunities. The area has route options. Road surface mostly sealed and reliable during the whole year period.
7 - 9	3	Moderate (average)	*Some restrictions of access* to a wide range of services and opportunities. The area has route options. Road surface partly unsealed but still reliable during the whole year period.
4 - 6	2	Low (remote)	*Restricted access* to a wide range of services and opportunities. The area has a limited route options. Road surface partly unsealed and may not reliable during the whole year period.
0 - 3	1	Very low (isolated)	*Very restricted access* to a wide range of services and opportunities. The area has a very limited option. Road surface mostly unsealed and not reliable during the whole year period.

Table 5. Scoring for each RNAI component

Score of component	Cut-off / threshold value		
	A_{rd}	C_{gf}	P_{ac}
5	> 0.7	> 0.9*	> 0.9**
4	> 0.4	> 0.8	> 0.8
3	≥ 0.2	> 0.6	> 0.6
2	≥ 0.1	≥ 0.4	≥ 0.4
1	< 0.1	< 0.4	< 0.4

*all arterial and collector road is in good/fair condition.
**all artery and collector road are sealed/paved.

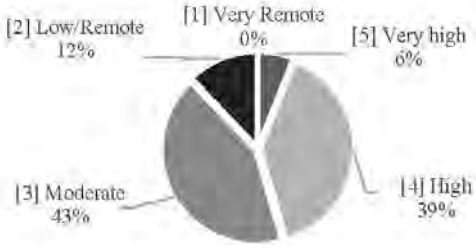


Figure 3. Accessibility in Indonesia year 2014 by province

5 MODEL APPLICATION USING HDM-4

To demonstrate how an economic model such as HDM-4 may be used to test the sustainability defined, data from Kalimantan Tengah Province of Indonesia was used (see Table 7). This also enabled the calibration of HDM-4 and its further use as follows. To test the existing accessibility, HDM-4 was run using the unconstraint budget option. The results in term of overall condition, i.e. roughness, are given in Figure 4 which explains that the existing accessibility does not ensure an acceptable level of the condition during the life cycle of the infrastructure (20 years). To test whether a budget constraint could affect the current accessibility, HDM-4 was run under a constraint budget of level 75 % of unconstraint budget. The results in term of condition, i.e. roughness, prove a noticeable effect of the budget constraint. To improve accessibility in Kalimantan Tengah Province, the unsealed road (gravel and earth road) should be upgraded into a sealed road, e.g. asphalt road. This scenario does not only reduce the overall surface roughness but also increase the reliability and sustainability of road service by improving pavement strength to withstand traffic and climate load. The impact of maintenance scenario corresponding to accessibility is given in Table 8.

Table 6. RNAI in Indonesia year 2014

Name of Province	Components			RNAI		
	A_{rd}	C_{gf}	P_{ac}	Σ_{Score}	Rating	level
Aceh	0.4	0.61	0.54	9	3	Moderate
Sumut	0.51	0.65	0.62	8	4	High
Sumbar	0.56	0.55	0.56	8	3	Moderate
Riau	0.3	0.73	0.49	8	3	Moderate
Kepri	0.69	0.66	0.65	10	4	High
Jambi	0.28	0.61	0.57	8	3	Moderate
Sumsel	0.19	0.71	0.61	8	3	Moderate
Kep. Babel	0.33	0.81	0.81	11	4	High
Bengkulu	0.44	0.60	0.60	10	4	High
Lampung	0.55	0.65	0.69	10	4	High
DKI Jakarta	10.55	0.64	1.00	13	5	Very high
Jawa Barat	0.71	0.65	0.86	12	4	High
Banten	0.71	0.70	0.82	12	4	High
Jawa Tengah	0.92	0.74	0.87	12	4	High
DIY	1.37	0.77	0.79	11	4	High
Jawa Timur	0.88	0.78	0.79	11	4	High
Bali	1.36	0.70	0.91	13	5	Very high
NTB	0.45	0.62	0.66	10	4	High
NTT	0.44	0.64	0.53	9	3	Moderate
KalBar	0.11	0.61	0.48	7	3	Moderate
KaTeng	0.10	0.60	0.41	5	2	Low
KalSel	0.32	0.68	0.62	9	3	Moderate
Kaltimut	0.08	0.71	0.45	6	2	Low
Sulut	0.65	0.63	0.67	10	4	High
Gorontalo	0.47	0.66	0.73	10	4	High
Sulteng	0.29	0.53	0.46	7	3	Moderate
Sulsel	0.70	0.65	0.53	9	3	Moderate
Sulbar	0.45	0.61	0.41	9	3	Moderate
Sultra	0.27	0.63	0.54	8	3	Moderate
Maluku	0.18	0.66	0.70	8	3	Moderate
Malut	0.22	0.49	0.77	8	3	Moderate
Papua	0.05	0.47	0.39	4	2	Low
Papua Barat	0.09	0.61	0.47	6	2	Low

Table 7. Road asset in Kalimantan Tengah Province year 2014

Road Asset	Road length by road status		
	National	Provincial	Regency
	km	km	km
Pavement type			
asphalt	1765	898	3170
gravel	237	116	1795
earth	0	81	6634
other	0	5	353
Condition			
good	1299	574	3068
fair	467	269	3295
poor (damage)	144	155	3752
bad (severe damage)	92	102	1837

Note: Land area for Kalimantan Tengah Province is 153,0564.5 square km.

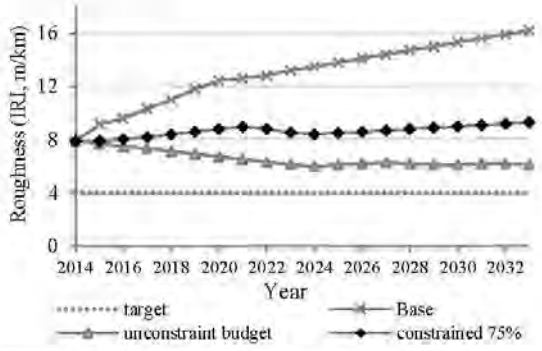


Figure 4. Budget effect on road performance

Table 8. Road maintenance scenario to increase accessibility in Kalimantan Tengah

Accessibility	Existing	Scenario		
		A1	A2	A3
Component				
road density (A_{rd})	0.10	0.10	0.10	0.10
condition (C_{gl})	0.60	1.00	1.00	0.70
pavement (P_{ac})	0.41	0.41	1.00	0.41
Value of RNAI				
Σ score	5	9	12	7
level	low	moderate	high	moderate

Note: A1: maximum preservation; A2: preservation and improvement (upgrade into asphalt road); A3: preservation with a medium budget (75%).

6 CONCLUSION

This paper has presented a methodology and a demonstration study that explains how a new accessibility index methodology may be defined and linked with an economic analysis tool (i.e. HDM-4) with the view to developing sustainable maintenance and development plans for the road infrastructure. It also illustrates how the condition of the road network may be optimised under budget constraints to achieve a level of accessibility that promotes economic development.

The RNAI model offers accessibility measurement which directly considers the road infrastructure and its economic life. The index parameter is linked with the HDM-4 input parameter. This ensures the target of accessibility is precisely interpreted from accessibility preference into a technical term of road asset management.

7 ACKNOWLEDGEMENT

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E.1.2 Presentation slide





Economic Optimisation of Road Network Accessibility

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Thessaloniki, Greece, June 2019

UNIVERSITAS GADJAH MADA
UNIVERSITY OF BIRMINGHAM
RISTEKDIKTI

BACKGROUND

Accessibility ?? In transportation, it refers to the ***ease to reach destinations***

→ **ISSUE**: **how** the term "**ease**" should be **defined** and **measured**

Why managing ***Accessibility*** *is Important?* → hampers economic and social development **FAILURE**



An appropriate road network management system should aim at achieving an optimum level of accessibility to all locations in need of transport services.

1. BIAS measurement of accessibility

Existing road infrastructure-based measurement only focus on **Road Density**
→ do not consider directly the **condition** of road and **its economic life.**

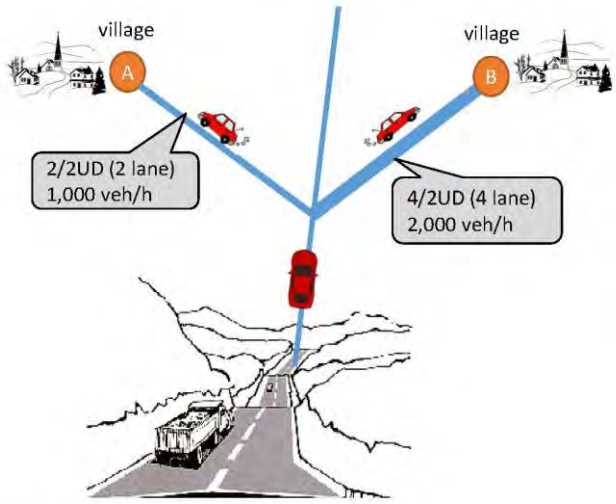




Condition ??

BACKGROUND

2. Budget allocation problem - DISPARITY



Example Case:

- Budget is always limited
- Both roads are important

Where should we spend our money?
village **A** or **B**

Based on **Economic analysis**

→ **always** village **B**

→ disparity of accessibility level increases

EQUITY…..???

IDEA

1. Add accessibility as decision criterion in managing road asset.
2. Develop infrastructure-based accessibility model

3

APPROACH

>> Road Infrastructure-based ACCESSIBILITY MODEL

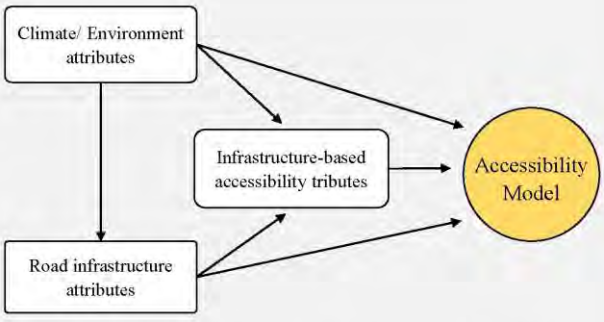


Figure 2. Attributes contributing to accessibility model



Figure 3. Accessibility model to link communication between stakeholders

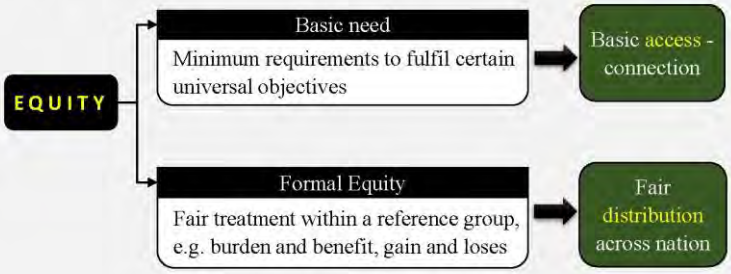
The concept of EQUITY

4

DEVELOPMENT OF ACCESSIBILITY MODEL

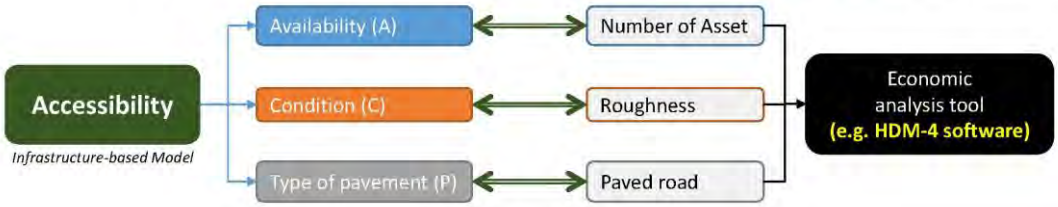
01 Theoretical framework

>> The concept of EQUITY



Dimension Indicators

Link with *Economic assessment* (integration)

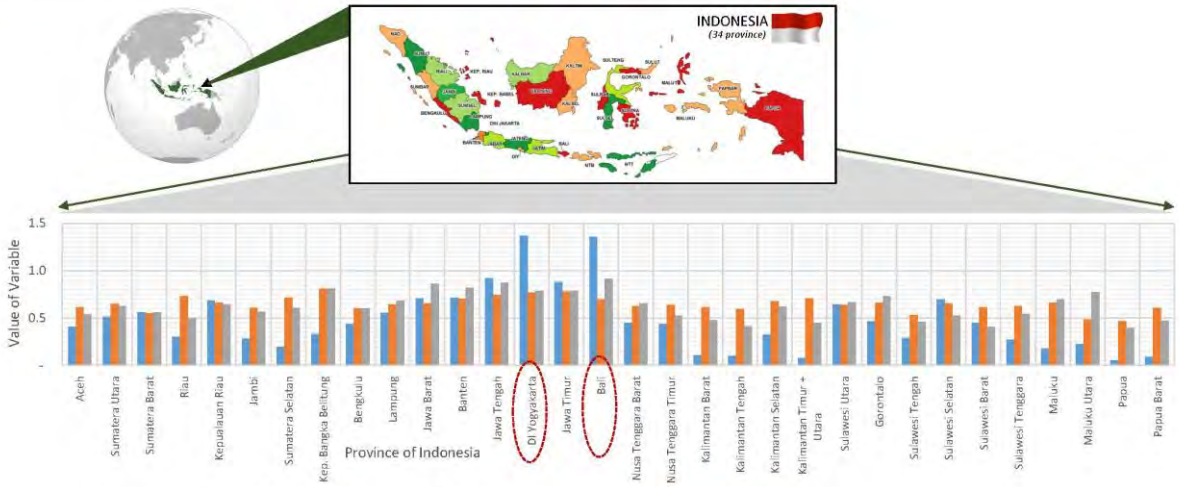


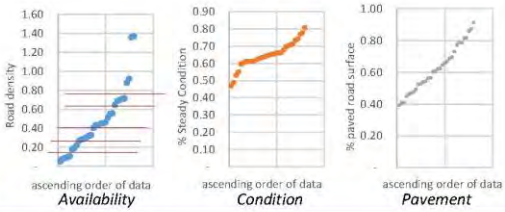
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DEVELOPMENT OF ACCESSIBILITY MODEL

02 Quantification

Back to Data: by province in Indonesia (year 2014)







Unit of analysis:
Provincial area

6

DEVELOPMENT OF ACCESSIBILITY MODEL

02 Quantification

Normalization

Scoring for each RNAI component

Score of component	Cut-off / threshold value A_{rd}	C_{gf}	P_{ac}
5	> 0.7	> 0.9*	> 0.9**
4	> 0.4	> 0.8	> 0.8
3	≥ 0.2	> 0.6	> 0.6
2	≥ 0.1	≥ 0.4	≥ 0.4
1	< 0.1	< 0.4	< 0.4

*all arterial and collector road is in good/fair condition.
**all artery and collector road are sealed/paved.

Aggregation

$$RNAI_{score} = Score\{A_{rd} + C_{gf} + P_{ac}\}$$

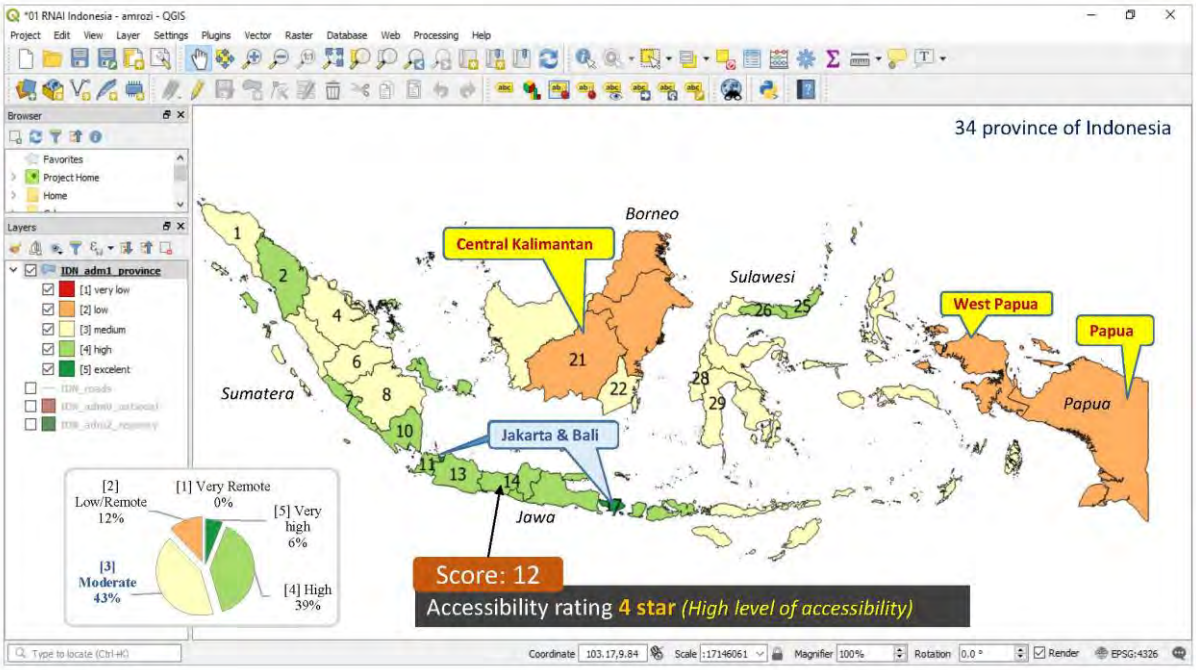
Ard : Road per Area [km / sq.km]
Cgf : Good + Moderate Ratio [km / km]
Pac : Paved Road Ratio [km / km]

RNAI score and meaning

Accessibility Σ Score	Star rating	level	meaning
13 - 15	5	Very high	unrestricted access (excellent)
10 – 12	4	High	Relatively unrestricted access
7 – 9	3	Moderate	some restrictions of access (average)
4 – 6	2	Low	Restricted access (remote)
0 – 3	1	Very low	very restriction access (isolated)

DEVELOPMENT OF ACCESSIBILITY MODEL

03 Presentation & Visualization

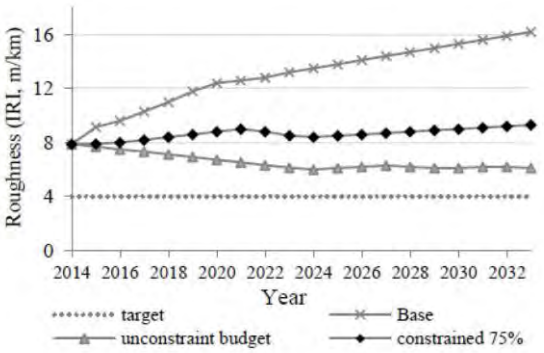


Case Study:
Kalimantan Tengah Province, Indonesia

Table 8. Road maintenance scenario to increase accessibility in Kalimantan Tengah

Accessibility	Existing	Scenario		
		A1	A2	A3
Component				
road density (A_{rd})	0.10	0.10	0.10	0.10
condition (C_{gf})	0.60	1.00	1.00	0.70
pavement (P_{ac})	0.41	0.41	1.00	0.41
Value of RNAI				
Σ score	5	9	12	7
level	low	moderate	high	moderate

Note: A1: maximum preservation; A2: preservation and improvement (upgrade into asphalt road); A3: preservation with a medium budget (75%).



1. Accessibility model may be defined and linked with an economic analysis tool, i.e. HDM-4 software.
2. Condition of the road network may be optimised under budget constraints to reach an optimum level of accessibility.
3. The application of RNAI may ensure the target of accessibility is precisely interpreted from accessibility preference into a technical term of road asset management.

Ευχαριστώ

Thank you *Terima kasih* *Danke dir* *Obrigado*

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E.2 2nd Annual SoE PGR Symposium, The University of Birmingham, Birmingham, UK, 16th July 2018

Road Asset Management Strategies to Adapt with Climate Change in Developing Country

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Abstract

Climate change affects a severe impact on road infrastructure over the last decade. For example, in Indonesia, through the extreme features such as increasing temperature, precipitation, wind speed and sea water level, climate change not only accelerate the deterioration of road pavement but also disrupt and even cut/damage the road access, for example, due to fallen trees, flooding or landslide. Based on engineering perspective, this threat may be solved by strengthen the road pavement and upgrade it into a robust infrastructure. However, because the cost is extremely expensive, this option is not feasible for developing countries that are struggling and barely manage road network performance with low maintenance budgets. In addition, each country has unique characteristics related to climate, road assets, maintenance standards, and resources. That makes adaptation strategies which typically developed in developed countries should be reviewed to meet the budget and local characteristics of developing countries. Therefore, this study tried to find out how developing countries, such as Indonesia, should manage their road asset under such conditions.

This study was conducted using literature reviews and lifecycle-cost analyses (LCCA) of road pavement with HDM-4 software as a decision support tool. The initial study was carried out by identifying pattern of climate change and its impact on road infrastructure. Some international best practices in climate change adaptation were then identified and assessed for the feasibility in accordance with available resources and technologies. Afterward, the HDM-4 model simulates the adaptation options using Indonesian road asset database and tropical climatic characteristics as a case scenario to ensure the practicality and cost effectiveness.

In term of road pavement in tropical countries, climate change increases the climate load on pavement mainly due to increasing precipitation and temperature. The HDM-4 model shows that the more robust/strength road pavement the more resistance road pavement to the climate exposure. For developing countries adaptation strategies, the lifecycle-cost analysis shows that not all road pavements in the road network necessarily should be upgraded as a robust infrastructure. The robust infrastructure and another infrastructure protection, such as cliff protection, only required for assets located in exposure/hazard area. Strategy to maintain road networks resilient by sealing road surface, using asphalt or cement, and preserving road condition at a certain range of standards are acceptable and satisfy both technical and economic requirements.

Keyword: *climate change, road asset management, developing country, robust, resilient, HDM-4*

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2nd Annual SoE PGR Symposium
Birmingham, July 2018

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Case Study: Indonesia

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Extreme weather- Climate change







Photo by Gunter Zietlow, 2001, GTZ



extreme weather condition

- Temperature
- Precipitation
- Wind
- Sea level

How to manage it ?

ROBUST road infrastructure
Increase strength → Rigid



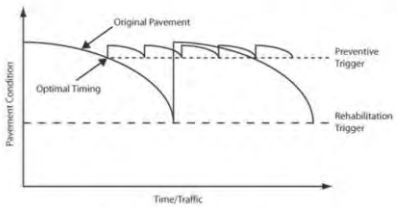


Budget is Low and limited



Cost-effective maintenance

- Adaptation (local) Scenario
- Lifecycle-cost analysis (HDM-4)



Source: www.fhwa.dot.gov

*Goes to **RESILIENT** road networks*

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2

Weather characteristics *in Indonesia*

Feature	Avg. Normal	Extreme
Temperature	27 °C	> 30 °C
Precipitation	2,000 – 3,000 mm/year	> 2,400 mm/year > 100 mm/day
Wind speed	0-40 km/h	> 60 km/h

Source: BMKG 2010

Decision Support Tools



FINDING This is where most preservation budget is lost...!!



- ✓ **The most climate threat is precipitation** < multiplier: damage, strength, delay, safety, accessibility>
- ✓ The stronger (**robust**) pavement design the more **resistance** of pavement to weather.
- ✓ **Sealed pavement** is more cost-effective and resistance to weather
- ✓ The **better road condition** the more resistance to weather (slower deterioration)

3

Adaptation Strategy - Policy

Engineering Policy	General Policy
1. **Promote sealed road** using more rut-resistance asphalt or concrete pavement. 2. improve **drainage system** 3. Enhance **protective infrastructure**: retaining wall, sea wall, etc. 4. Plant and maintain **roadside vegetation** 5. Increase **routine** maintenance	1. Provide more resilient design standard and material 2. Create vulnerability map to identify risk area and vulnerable infrastructure 3. Create resilient system by build a new road as alternative road for vulnerable road segment. 4. Restrict/avoid development in high risk area 5. Possible retreat or abandon infrastructure in high risk area.



earth road

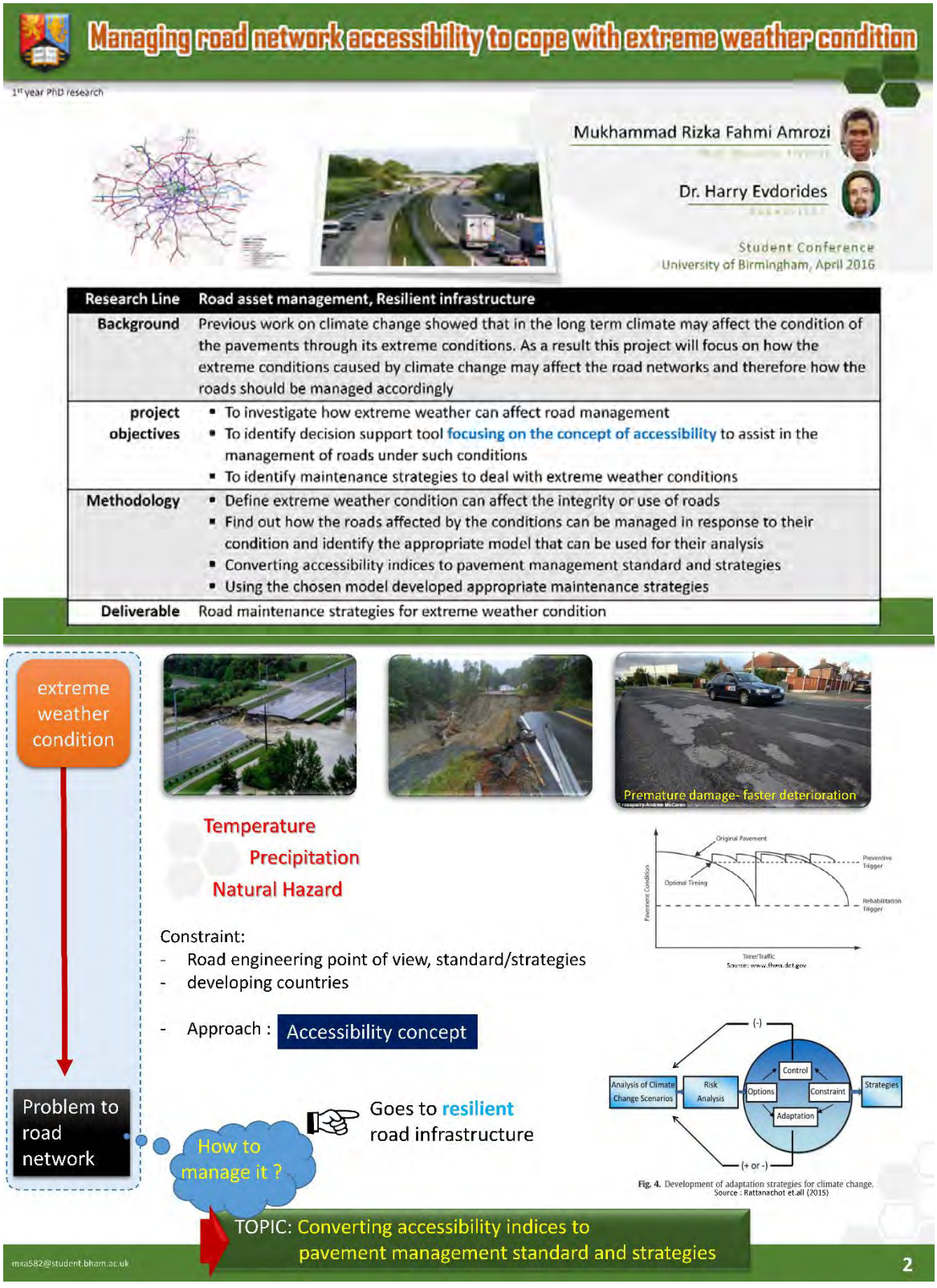


Wheel Track Paving Strip Roads

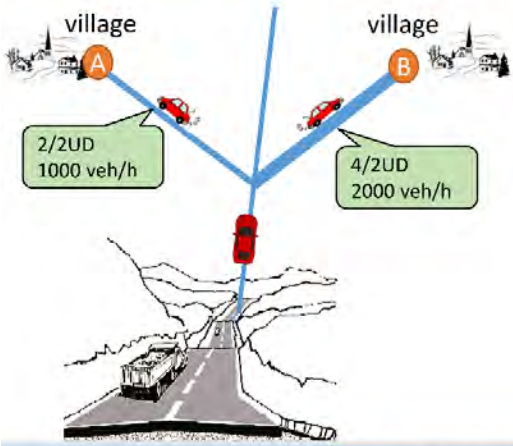
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E.3 Student conference 2016, The University of Birmingham, Birmingham, UK

Presentation slide of student conference 2016



Budget allocation problem



Example Case:

- Budget is always limited, *e.g. barely enough for one road*
- Both roads are important,

Where should we spend our money? village **A** or **B**

Based on Economic
Benefit Cost analysis → **always** Village **B**
EQUITY…..???

The idea - introduce **ACCESSIBILITY Concept**

In transportation, accessibility refers to the ***ease of reaching destinations***.

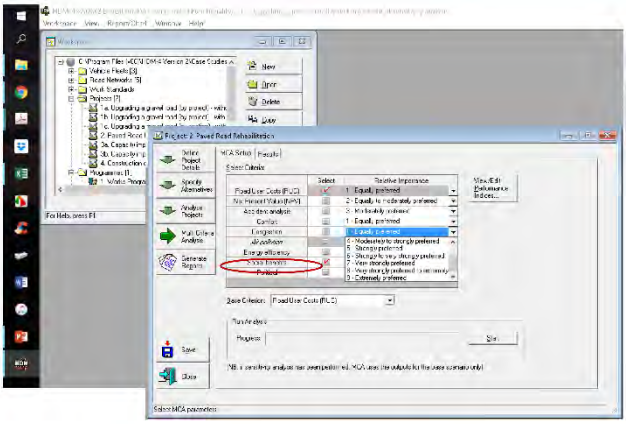
→ **ISSUE**: **how** the term "**ease**" should be **defined** and **measured**.



Accessibility Indicator
Min = 0 % → worst
Max = 100 % → best

Availability
Quality
Opportunity and mobility
Equity
Perceived value from road infrastructure performance

Decision Support Tools



HDM - 4
HIGHWAY DEVELOPMENT & MANAGEMENT

STRATEGY

- ❖ use economic + accessibility indicator for budget allocation
- ❖ set/develop maintenance standard

LINK Road infrastructure **accessibility model**
with **HDM-4** as decision support tools