A SEMI-EMPIRICAL FRAMEWORK TO INTEGRATE ROAD SAFETY AND ROAD ASSET MANAGEMENT INVESTMENT APPRAISAL

by

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Abstract

A Semi-Empirical Framework to Integrate Road Safety and Road Asset Management Investment Appraisal

The current most advanced road investment appraisal tool has comprehensively associated with the detailed pavement life-cycle models. It is believed that road safety aspects may add value to the road investment appraisal tool that considers both road asset management and road safety management.

The main objective of this research was to integrate the road safety model and road asset management model that maximise benefits to road users and stakeholders. The available road safety and road asset management models have been examined to determine their compatibility and potential integration. A road safety life-cycle model which consists of the Road Safety Degradation (RSD) model and the Countermeasure Effects (CE) model has been developed to appropriately integrate both road safety and road asset management models. The road safety life-cycle model was validated using the existing database that has been collected in 2007 for the International Road Assessment Programme (iRAP) pilot project in Malaysia provided by the Malaysian Institute of Road Safety Research (MIROS). The results from the validation procedure have shown that there is a significant relationship between pavement life-cycle models and the road safety life-cycle model.

The validated road safety life-cycle model was then used in a detailed parallel assessment of road safety and road asset performance. The evaluation procedure was carried out as a case study to investigate the performance of road network in terms of road safety and road asset management throughout the period of analysis. The case study was designed in three

implementation strategies appropriate to the evaluation options available in the Road Network Evaluation Tools (RONET). The RONET was used as the automatic operation to evaluate the road asset performance in terms of roughness. However, the road safety performance was evaluated in the manual operation using Microsoft Excel (MS Excel) spreadsheet. The results of the parallel assessment have demonstrated that the integration method that was proposed is an ideal tool to integrate road safety and road asset management investment appraisal.

(Keywords: integration, road safety, road asset management, life-cycle analysis, road economics)

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Dedication

Special dedication to:

My wife and kids who are the source of inspiration and support throughout the seasons.

My mentors who are always there to advise and guide me throughout my career.

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List of Abbreviations

AADT	Average annual daily traffic
ADT	Annual daily traffic
ASR	Average Star Rating
B/C	Benefit/Cost ratio
CE	Countermeasure effect
CEM	Countermeasure Effects Model
CEI	Countermeasure Effects Index
CMF	Crash modification factor
CMFC	Crash Modification Factors Clearinghouse
dIRI	Deviation of International Roughness Index
dRSR	Deviation of Road Safety Rating
dSRS	Deviation of Star Rating Score
ESRS	Equivalent Star Rating Scores
GDP	Gross Domestic Product
HDM	Highway Development and Management
HDM-4	Highway Development and Management Tools (version 4)

iRAP	International Road Assessment Programme
IRI	International Roughness Index
JKR	Public Works Department of Malaysia
KISB	Kumpulan Ikram Sdn Bhd
MS	Microsoft
NPV	Net present value
PAM	Performance Assessment Model
PIARC	World Road Association
RE	Roadwork effect
REAM	Road Engineering Association of Malaysia
RONET	Road Network Evaluation Tools
RSDI	Road Safety Degradation Index
RSR	Road Safety Rating
SN	Structural Number
SRS	Star Rating Score
SRT	Safer Road Treatment
VOF	Value of fatality
VOI	Value of injury

VSL Value of Statistical Life (VSL or VoSL)

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CHAPTER 1

INTRODUCTION

1.1 Background

Based on the Global Status Report on Road Safety 2015 published by the World Health Organisation (WHO), about 1.25 million fatalities are recorded every year as the result of road traffic accidents. Road traffic accidents have been identified as a public health issue as it becomes the major cause of death among young people below 30 years old. The cost of accidents is estimated at around 3 per cent of the gross domestic products (GDP) of most countries. This has also become a major concern with more than 90 per cent of global road traffic deaths occurs in developing countries which are considered as low and middle-income countries (LMIC).

In 2011, WHO has initiated a global framework to reduce the rate of road traffic fatalities around the world with the establishment of the Decade of Action Plan for Road Safety 2011-2020. This effort has been translated from the Global Status Report on Road Safety 2009 to set a long-term target to reduce road accident fatalities by 2020 (World Health Organisation, 2011). The consecutive report in 2013 and 2015 showed that the trend of road traffic fatalities rate globally has plateaued since 2009 at around 1.2 million per year despite an increase in vehicle ownership and total population. This may conclude that all the efforts made to tackle road traffic fatalities are effective which if more extensive implementation will affect a more convincing result (World Health Organisation, 2009 & 2013).

Many effective countermeasures have been taken to curb road accident problems with the main objective to reduce fatalities and injuries rates. However, the implementation of these countermeasures on an appropriate scale is mostly focused on developed or high-income countries. Meanwhile, the low and middle-income countries are struggling to tackle this issue due to a lack of funding. As the road management funds are limited, road safety countermeasures have always been chosen to be dismissed to make way for the presumably higher priority road maintenance programmes.

Globally, funding issues among developing countries have reduced the effectiveness of road safety countermeasures in eliminating worldwide high-risk roads to safer road infrastructure. Therefore, there is a demanding need to develop a road safety investment appraisal tool that could provide decision support for road managers in managing road safety issues. On the contrary, the use of road investment appraisal tools for road assets management and maintenance has long been widely used by road managers worldwide.

Road investment appraisal tool plays a vital role in road asset management. The main objective of road investment appraisal tools is to analyse the scale of investment alternatives and prioritise the alternatives based on certain criteria. This can help to strategically and economically manage limited road funding to maximise the benefits. The analytical framework of such a tool is based on economic evaluation parameters. One of the most advanced tools such as the Highway Development and Management Tools (HDM-4) uses life-cycle cost and condition prediction in its analysis. The analysis may consider all associated costs such as construction costs, maintenance costs, as well as depreciation costs resulted from road deterioration. It may also reflect road safety aspects in the analysis but there are reasons to believe that a more explicit road safety management approach may be considered as added value for wider applications.

As well as the road management appraisal tool, a road safety investment appraisal tool is required to analyse the technical and economic aspect of road safety countermeasures to prioritise and maximise the investment in road safety. Currently, several road safety management tools may provide a platform for assessing road safety condition and analysing the road safety investment plan. However, the available road safety management systems can be considered very premature if we are to compare them with many other road assets management systems.

Ideally, a road safety appraisal tool should also consider available economic models similar to the one that is widely applied in a more advanced road management investment appraisal model. This is significant when considering the limitation of funding to improve road safety features either for the construction of a new road or upgrading of the existing road network as well as for road maintenance. Furthermore, it will be more complicated when both road safety and road maintenance need to be considered at the same time. Therefore, an integration of both investment appraisal may provide a better investment option.

The integration of both appraisal tools for road asset and road safety may provide a harmonised system and may also help to reduce redundancy on certain treatments or countermeasures. Comparing both appraisal tools, the economic analysis model used in the road safety appraisal is very basic as it only considers the direct cost of treatment and benefits from casualties prevented. Considering this, the road safety appraisal may need a more advanced economic analysis model to enhance its protocol. This may include performing the life-cycle analysis that not only consider the direct cost and benefit but also the fluctuation of performance and the effectiveness of countermeasures in its analytical framework.

Enhancement to the economic analysis model in the current road safety appraisal is crucial to ensure that its protocol is easily accepted in developed or developing countries. In this study,

available roadworks and countermeasures will be reviewed to enhance the total road asset management model which considers the effectiveness and life-cycle of treatment for both road safety and road maintenance works. This study is expected to integrate the road asset management and road safety investment model and will include the life-cycle analysis as the basis of the economic analysis. With this enhancement, strategic analysis of road investment appraisal will be more objective in terms of technical and economical aspects.

1.2 Problem Statement

Malaysia is one of the developing countries that has been fighting road safety issues. The increasing number of registered vehicles has been contributing to the significant numbers of road traffic accidents. As the number of road users increased, the road network has been suffering from a maintenance backlog. To tackle both road safety and road asset management issues, the road authority in Malaysia has to apply two separate road asset management and road safety management systems in their long-term road asset management programme.

The application of two separate roadwork programmes has caused an increasing demand for their limited road asset management funding. However, this effort may lead to a requirement of additional road funding as both systems are being analysed separately which may be subjected to other problems such as budget constraint, duplication of projects, overlapping of projects and redundancy. Due to limited funding, the road authority may opt to control the size of the investment which will increase the backlog of road safety and road maintenance issues. On contrary, if there is a surplus of funding, the road authority may tend to spend on unnecessary road investment projects.

To date, there is no established method that can be used to integrate both models to achieve the most effective solution. Therefore, there is an urgent need to establish such a method that can

help road asset managers to implement total asset management that tackles both issues of road condition and road safety collectively.

1.3 Research Questions

The research questions for this study are listed down as follows:

i. What are the effects of road maintenance works on road safety level?
ii. What are the effects of road safety countermeasures on road condition?
iii. What are the effects of a different roadworks implementation strategy on the road condition and road safety level?
iv. How to integrate road maintenance works and road safety countermeasures as a collective road assets management model that is measurable to be used in predicting future conditions, planning future works and monitoring the performance?

1.4 Aim and Objectives

This research will review the current progress that has been achieved in the development of the currently available road safety management system relative to the most advanced road assets management system. This research aims to integrate the road safety management model with the road asset management model as a more advanced road safety economic appraisal tools. The objectives of this study are as follows:

i. To examine compatibility for potential integration between available road safety models and road investment models in term of economic analysis;
ii. To identify methods for integration of road safety and road asset management assessment programme that maximise the benefits of road users and road agencies;

iii. To develop a more advanced economic life-cycle analysis model for the implementation of the road assessment programme; and

iv. To develop a robust road safety investment model for accident and casualty reduction in developing countries.

To address the lack of funding issues in road management especially related to road safety enhancement, it is intended to have an integrated approach for road assets management and road safety management. This research will further examine the compatibility between available systems in both areas of road management and will identify the potential integration methods. Practically, road safety countermeasures can be implemented together with other road assets management programmes. This research will examine the effects of an integrated approach for road safety countermeasures implementation into road maintenance programmes with regards to road condition and road safety level of the selected road networks. In other words, it is a significant achievement for all road managers if we manage to develop an integrated management system that assesses the road condition and road safety level of networks throughout the analysis period.

1.5 Significance of Research

The application of investment appraisal tools plays a vital role as decision support for road managers to prioritise road asset management programmes. Most of these investment appraisal tools are associated with detailed pavement life-cycle models. They may predict the deterioration rate of road assets and the performance of road assets based on a different level of budget strategy.

It is envisaged that these investment appraisal tools may also evaluate the performance of road assets in terms of road safety level. This will help the road managers to identify the relationship

of road management programmes, which referred to road development, upgrading and maintenance work, relative to road safety countermeasures in terms of roughness index as well as road safety index. Therefore, this research project will explore the possibility to integrate road asset management and road safety models in the investment appraisal tools.

The findings of this study will establish a life-cycle model for road safety which may explain the performance of road safety. This research will explore the methodology to replicate the pavement life-cycle model in terms of road safety behaviour. This will help the road managers to further understand the behaviour of road safety when the road assets are deteriorating as well as the scale of effectiveness of road safety countermeasures.

Ultimately, the integration of road safety and road asset management model will enable the road managers to enhance the overall road assets management programme which simultaneously tackles both road maintenance and road safety issues by optimising the benefits of available budgets. Consequently, this study may help road managers with their road management programme to reduce the number of a road accident and road fatalities which will directly benefit the road users.

1.6 Thesis Structure

This thesis is the presentation of the whole research that has been carried out to achieve the above aim and objectives of this research. The thesis has twelve chapters that represent eight main sections as shown in **Figure 1.1**.

CHAPTER 1 is the introduction section of this thesis which explains the background of the whole research, problem statement, aim and objectives of the research and the significance of this research. It also describes the structure of the thesis.

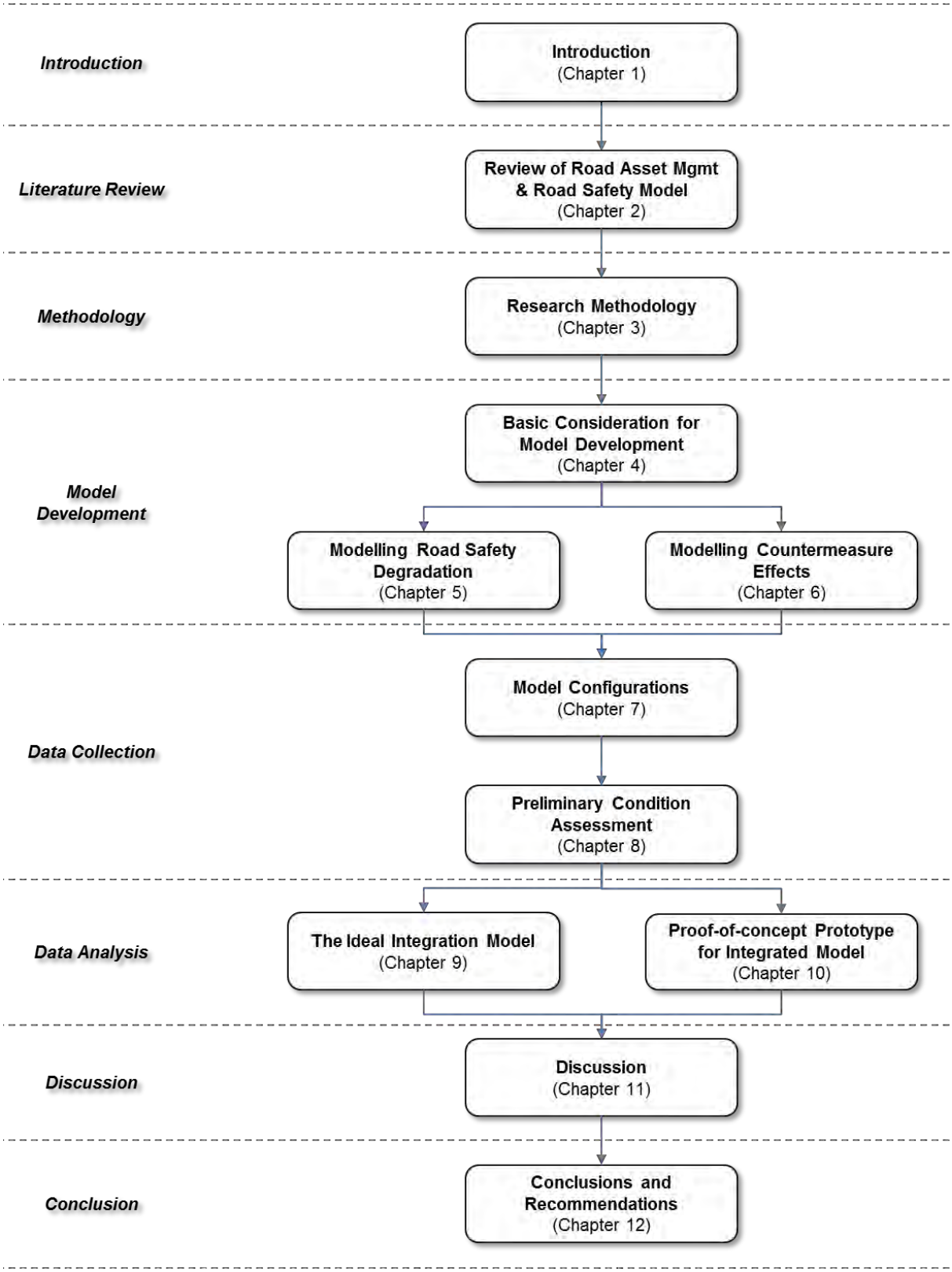


Figure 1.1 Thesis structure

CHAPTER 2 presents the critical literature review that was carried out throughout the research. There are several research publications, textbooks, manuals and handbooks that have been reviewed to establish the ground of the existing knowledge.

In **CHAPTER 3**, the overall methodology used in this research is explained. This chapter explains the theoretical aspects of this research to justify the design of the research framework as part of the integration process. It is divided into several subchapters to briefly introduce the idea to developed two submodels involved in the integration process namely the Road Safety Degradation Model and the Countermeasure Effects Model.

The model development section consists of three chapters. **CHAPTER 4** explains some basic considerations for the model development, the modelling theory, the assessment tools and the limitations of the proposed model.

In **CHAPTER 5,** the development of the Road Safety Degradation Model will be presented. The road safety Star Rating system that is used widely throughout this research will also be introduced in this chapter. A sensitivity analysis is carried out in this chapter to evaluate the change of Star Rating relative to the deterioration of the asset as part of the approach to develop the model.

CHAPTER 6 further explains the development of the second submodel namely the Countermeasure Effects Model. This chapter will review all the available roadworks and treatments applicable to development, maintenance and road safety projects. Another sensitivity analysis is carried out to rank the countermeasure based on a proposed index. The development of the Road Safety Degradation Model and Countermeasure Effects Model is the main output of this research which will be validated later.

The data collection section is presented in two chapters. **CHAPTER 7** mainly explains the configuration of the assessment model that is used in this research. A brief introduction of the study area in Malaysia is presented in this chapter. The model configuration is carried out based on the network information and characteristics of the study area. The data presented in this chapter are the common data collected in Malaysia which will be used later in the assessment model.

The preliminary results from the data collection and road assessment programme are presented in **CHAPTER 8**. This chapter will also discuss the quality of data that may be gathered from the data collection exercise and how to deal with different data quality. In this chapter, a sensitivity analysis was carried out to validate the Road Safety Degradation Model as presented in Chapter 5. The relationship of roughness that represents road asset condition and road safety level was validated in this chapter based on the collected data.

The data analysis section is divided into two chapters. The integration architecture and the prioritisation approach are discussed in details in **CHAPTER 9**. The background of the case studies and the design justification are also presented. The relationship between road asset deterioration and road safety degradation is examined and discussed in details at the end of this chapter.

It is followed by the application of the concept where the overall result of the analysis will be presented in **CHAPTER 10** as a complete case study for the prototype testing of the integrated model. The impact of all implementation strategies will be analysed and presented in this chapter together with the economic analysis as a complete workable decision-support tool.

The discussion of the whole thesis, from the introduction to the result of the prototype model data analysis, will be presented in **CHAPTER 11**. Applications and transferability of the model

are also discussed, focusing especially on issues related to the application in Malaysia. The challenges and limitations of this research are also presented at the end of this chapter.

CHAPTER 12 is the concluding section of this thesis where the conclusions are presented. There will also be recommendations for future research presented in this chapter.

1.7 Academic Contributions

Two papers were presented related to this research as follows:

i. Azmi, A.E., Evdorides, H. 2017. Maintenance Programmes to Manage High-Risk Roads. XV. European Transport Congress & X. International Road Congress. European Platform of Transport Sciences (EPTS). Budapest, Hungary.

ii. Azmi, A.E., Evdorides, H. 2019. Life-Cycle Safety Rating of Road Maintenance Works. Proceedings of the 7th International Conference 'Bituminous Mixtures and Pavements' (7ICONFBMP). Thessaloniki, Greece. DOI: 10.1201/9781351063265-91.

During the academic year, this research has also participated in several activities and was awarded as follows:

i. Winner for the College of Engineering and Physical Science at the University of Birmingham Research Poster Conference 2017 on 15 June 2017.

ii. Runner-Up at the University of Birmingham Image of Research 2018.

1.8 Conclusion

This chapter has presented the introduction section of the thesis which explains the problem statement, aim and objectives of the research. It also explains the structure of the thesis.

CHAPTER 2

REVIEW OF ROAD ASSET MANAGEMENT AND ROAD SAFETY MODEL

2.1 Introduction

This chapter will present the critical literature review related to road management and road safety model that has been carried out throughout the research. There are several research publications, textbooks, manuals, and handbooks that have been reviewed. The literature review will look into some key problems discovered by other researchers that bother road safety and how the road investment appraisal may offer a solution to tackle road safety issues. The economic aspect of road accidents is also discussed concerning the relation to road pavement models. Some studies related to the integration of road asset management and road safety model are also reviewed. Finally, this chapter will compare the existing road asset management and road safety models to identify the gap between them that may be explored.

2.2 Key Road Safety Management Issues and Challenges

Based on World Health Organisation (WHO) report, only 10% of casualties related to road accidents occurred in high-income countries while the remaining 90% occurred in developing countries (Peden et al., 2004) while about 50% of fatalities involved the vulnerable group of pedestrians and cyclists. This situation can be related to a lack of funding and lack of implementation of road safety programmes in low and middle-income countries (LMIC).

Issues on road safety programme implementations are not only related to physical road safety infrastructures such as pedestrian crossing, cycle-lane, traffic light, and traffic signage but also as a coordinated system between all stakeholders as a whole including implementation of the law, education, vehicle safety, and funding. **Table 2.1** shows the comparison of estimated global road traffic injury-related deaths between low and middle-income countries to high-income countries. The injury rate per 100 thousand population in low and middle-income countries is almost twice of high-income countries. Globally, the proportion in low and middle-income countries is about 90% out of the total road traffic injury-related deaths recorded. This is a piece of statistical evidence that shows the extent of the problem within these countries.

Table 2.1 Estimated global road traffic injury-related deaths.

Country Income Range	Number	Rate per 100 000 population	Proportion of total (%)
Low-income and middle-income countries	1 065 988	20.2	90
High-income countries	117 504	12.6	10
Total	**1 183 492**	**19.0**	**100**

(Source: Peden et al., 2004)

Figure 2.1 shows the issues related to road safety that have emerged in several African countries. Assum (1998) has discovered that road safety issues are a cyclic problem and require four aspects to be fulfilled which are a political concern, funding, implementation, and accident reduction. In other words, if the political will is increased, appropriate funding will be made ready by the road authority to implement road safety programmes which will consequently

reduce the accident. It is believed that the cyclic model may explain the achievement of high-income countries to curb road traffic accidents and the failure of low and middle-income countries to manage this problem.

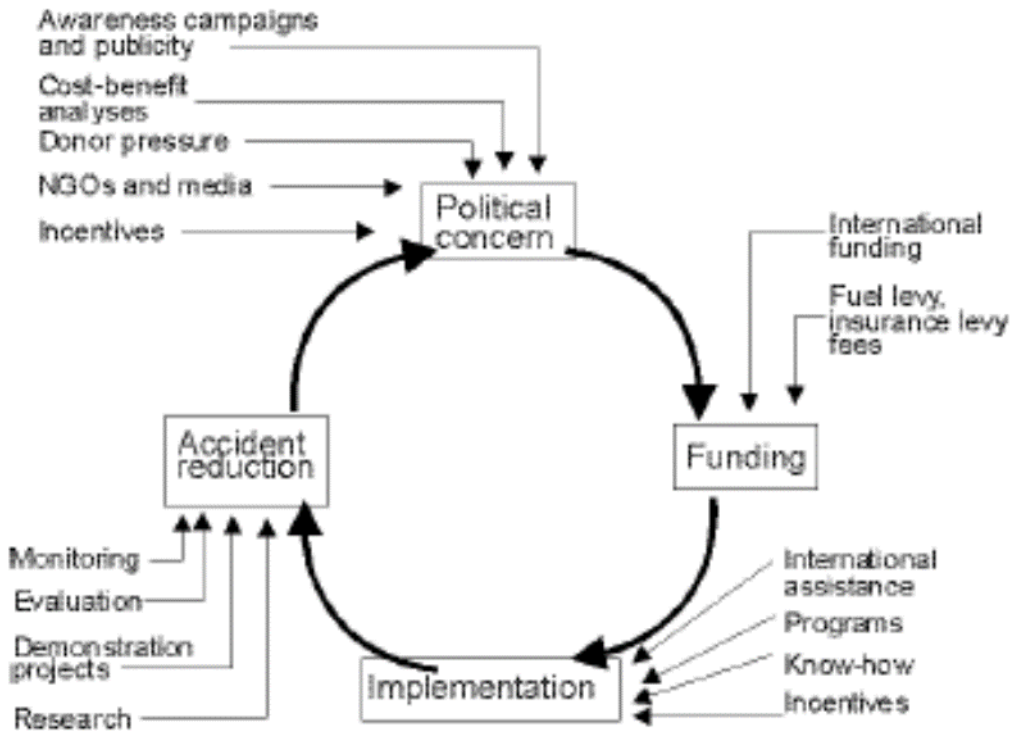


Figure 2.1 Basic requirements to sustained road safety and ways to fulfilling them

(Source: Assum, 1998)

WHO has recommended six recommendations to be implemented in all countries as part of the initiatives to reduce road accident casualties as below (WHO, 2009):

i. To identify a lead organisation in guiding national road safety programme;

ii. To assess the issues, policies and institutional arrangement related to road safety in each country;

iii. To prepare a road safety plan at the national level;

iv. To prepare the required resources to address all issues;

v. To implement suitable actions to reduce road accidents;

vi. To support international cooperation on road safety.

WHO (2009) has also highlighted that the six recommendations can be initiated when appropriate data of accident and road safety conditions are available. The need to record and document such data has now become a basic requirement. Unfortunately, it is reported that many low and middle-income countries lack sufficient data that are required for proper road safety management.

It is believed that a proper road safety management system that can manage all the road safety data may offer a fundamental solution to the four basic requirements to sustained road safety as highlighted by Asum (1998). This system will encourage creating awareness to boost political concern, carry out the cost-benefit analysis, justify the amount of funding requirement, manage the road safety implementation programmes and monitor the effectiveness of the overall plan.

Therefore, the International Road Assessment Programme (iRAP) is now available to help developing countries as well as developed countries to collect road safety condition data and to perform road safety assessments for their road network (WHO, 2013). The iRAP is the umbrella programme for Road Assessment Programmes (RAPs) worldwide that are working to save lives from road deaths and injuries.

The iRAP has developed an integrated protocol to help partners across the world in solving road safety issues. The protocol consists of Risk Mapping, Star Rating, Safer Roads Investment Plans and Policy and Performance Tracking tools (iRAP, 2014a). iRAP protocol has helped

many countries to do a road safety inspection and produce star rating for the accident risk assessment of road networks as well as prioritising the road safety treatments as a road investment appraisal (WHO, 2009, 2013).

2.3 Road Investment Appraisal

The main function of a road investment appraisal is to calculate the total transport costs which consist of the road construction, road maintenance and road user costs for a specified analysis period. A road investment appraisal model may be used as a decision-support tool to assist in the selection of appropriate road design and maintenance standards that minimise the total transport costs. It may provide an economic evaluation to select projects with high economic returns (Odoki and Kerali, 2000).

According to Odoki and Kerali (2000), the primary objectives of road investment appraisal can be summarised as follows:

i. To determine the appropriate size of road investment and the expected returns from the investment,
ii. To determine the appropriate design standards for the size of road investment to obtain the expected returns,
iii. To determine the priorities among road investment options relative to budget constraint, and
iv. To assess the overall economic costs and socio-economic impact of road investments.

A road investment appraisal is used to identify the total transport cost, which consists of road agency cost (RAC), and road users cost (RUC). The appraisal should provide a relationship of these costs which correlate to another to identify the required size of the investment. As for an

established road investment appraisal, Highway Development and Management Tools (HDM4) can be considered as the most advanced system available as it was developed and recognised by the World Bank. Other road investment appraisals developed under the World Bank organisation are the Road Network Evaluations Tools (RONET), Road User Costs Knowledge System (RUCKS), Road Costs Knowledge System (ROCKS), Roads Economic Decision Model (RED) and Roads User Charges Model (RUC).

Based on the Highway Development and Management Toolkit (HDM4) model, Odoki and Kerali (2000) suggested that transport cost has a unique relationship with pavement standard which also can be associated with road standard and road condition. In general, as the road standard gets higher, the road agency cost will be increased whereas road users cost will be reduced. To minimise the total transport cost, this model may provide the optimum road standard which can be adapted as the most economic road investment. **Figure 2.2** shows the optimum road standard which can be derived based on the components of total transport cost.

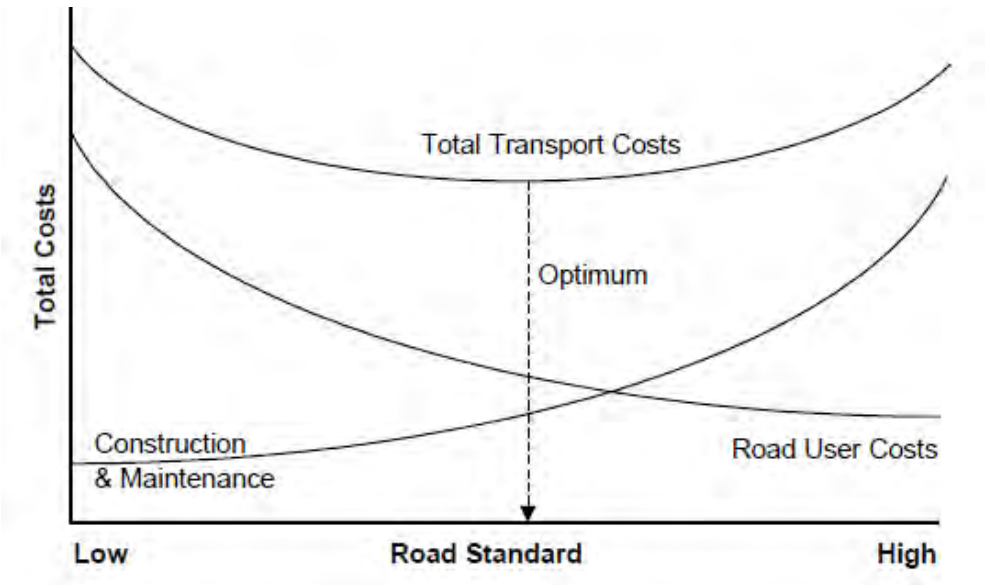


Figure 2.2 Optimum road standards derived from total transport costs

(Source: Odoki and Kerali, 2000)

From the total transport cost, the components that become the road agency cost are the construction and maintenance costs of the infrastructure. For road users cost, it is comprised of vehicle operating costs, travel time costs, accident costs and environmental costs. To further develop the integration of the road safety model and road management model, the following subchapter will look into the accident costs component that may reflect the total transport cost.

2.4 Accident Cost Estimation Methods and Application in Road Investment Appraisal

Robinson and Thagesen (2004) and Jacobs (1995) emphasized that Hills and Jones-Lee (1981, 1983) have identified six different methods to evaluate road accident cost applicable to non-fatal as well as to fatal accidents as shown in **Table 2.2**.

Jacobs (1995) has concluded that the main reasons for evaluating the road accidents cost are most likely to be either to maximise the national output or to fulfil the social welfare objectives. Therefore, the most suitable accident cost evaluation methods that appear to be directly relevant to these two objectives are the Gross Output (or Human Capital) method which well suited to the objective of maximising the wealth of a country and the Willingness-to-pay method which well suited for social welfare maximisation and use in cost-benefit analyses.

There are some differences in how accident cost is being applied in the road investment appraisal model. In HDM4, as explained in the earlier section, accident cost is a component of road users cost which will be added up to the total transport cost when construction and maintenance costs are added up. According to Odoki et al. (2000), the earlier version of HDM4 adopted a “look-up tables” approach where accident rates are given as a function of key data relative to traffic volume and road width.

Table 2.2 Accident cost evaluation method

Approach	Features
Gross Output (Human Capital)	• Loss of current resources and future output • 'Pain, grief and suffering' of victims and those who care
Net Output	• Similar to the Gross Output approach with a discounted value of 'future consumption'
Life Insurance	• Cost of life insurance value
Court Award	• Cost awarded to the dependants of victims
Implicit Public Sector	• Cost of accident prevention value in safety legislation
Value of Risk Change (Willingness-to-pay)	• Amount that public willing to pay for a road safety improvement

(Source: Adapted from Robinson and Thagesen (2004) and Jacobs (1995))

It was assumed that any changes to these will correspond to changes in accident rates. This approach is likely to be an accident prediction even though it was claimed that HDM4 does not predict accident rates. In HDM4 version 2.0, accident cost is adopted directly as the annual cost of the accident. In its economic analysis module, Multi-Criteria Analysis could be performed to increase the preferred criteria such as road safety or even seven other subjective criteria.

Archondo-Callao and Faiz (1994) did not include accident cost as part of the transport cost components when they first introduced the method of estimating road users cost. This method which has been recognised and adopted by World Bank in HDM4 was later expanded to include accident cost and environmental cost to the existing capital and physical-based of road users cost. In 2010, Archondo-Callao presented that the HDM-4 Road User Costs Model Version 2.0 with an adaptation of the iRAP methodology for estimating road safety cost of fatality and serious injury.

An accurate estimate for accident cost in each country will require a proper survey but will be costly especially in developing countries where accident data are lacking and questionable. Therefore, McMahon and Dahdah (2008) have taken the lead to establish the accident cost in the iRAP methodology. This cost was derived from an empirical estimation of several existing studies in developed or high-income countries. This is to verify the study by Alfaro et al. (1994) that the cost of an accident can be estimated by variation of gross domestic product (GDP) per capita.

McMahon and Dahdah (2008) have examined the accident cost based on the value of statistical life to value the benefit of countermeasures implementation in preventing road accident fatality. McMahon and Dahdah (2008) claimed that this value is important to weigh the economic benefit of road safety investment in the iRAP methodology.

In the iRAP methodology, accident cost which refers to the Value of Fatality is used to identify the economic benefit of accident prevention in the economic assessment as mentioned by McMahon and Dahdah (2008). The economic benefit is given in the following formula:

The economic benefit =

(number of fatalities prevented x 70 x GDP per capita)

+ (number of serious injuries prevented x 0.25 x 70 x GDP per capita) (**2.1**)

Two methods that have been examined for this purpose is the Human Capital or Lost Output method and the Willingness-to-pay method. This is aligned with the proposed method by Jacobs (1995), who suggested in the Overseas Road Note 10 (ORN 10) that these two methods

are the most directly relevant to maximisation of national output and minimisation of accident effects.

As these two methods are being adapted differently by each country, values of statistical life are relatively different for each country in some range. Based on McMahon and Dahdah (2008) investigation, they have come out with a simple empirical rule-of-thumb approach to be used in iRAP methodology. In the iRAP methodology, the value of fatality can be calculated based on 60% to 80% of gross domestic product (GDP) per capita of a country while the value of serious injury is between 12% to 24% of GDP per capita. **Table 2.3** shows the iRAP economic appraisal model values based on the Rule-of-thumb approach.

Table 2.3 The iRAP economic appraisal model values

	Lower	**Central**	**Upper**
Value of Fatality	60*GDP/Capita	70*GDP/Capita	80*GDP/Capita
Value of Serious Injury	12*GDP/Capita (20%VSL)	17*GDP/Capita (25%VSL)	24*GDP/Capita (30%VSL)
Number of Serious Injuries to number of Fatalities	8	10	12

(Source: McMahon and Dahdah, 2008)

In general, it is clear that both road investment appraisal models, HDM4 and iRAP, use accident cost differently in their analytical model. To identify which approach is the best option to be applied in the road investment appraisal model, the concept of benefit need to be understood.

Stubbs et al. (2017) has suggested that the benefit in road investment can be explained with the Demand Curve theory (Price Elasticity of Demand) as shown in **Figure 2.3**. This theory

explained that traffic is inversely proportional to cost. This means that a positive road investment will be benefited from the reduction in transport cost (indicated by the yellow area of the graph) and increment in generated traffic (indicated by the green area of the graph).

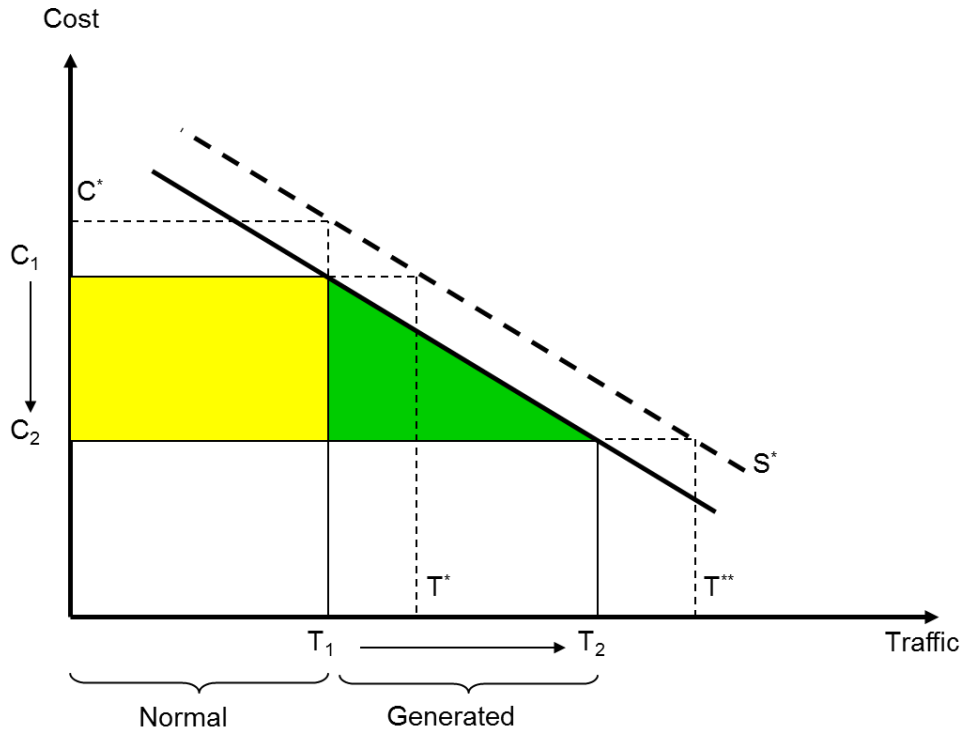


Figure 2.3 Demand Curve theory (Price Elasticity of Demand)

(Source: Stubbs et al., 2017)

From the Demand Curve theory, it may be suggested that if safety improvements are invested by the authority at a certain cost beyond the construction and maintenance cost, the demand line will move to the right as indicated by *S**. Taking this new demand line into consideration, the amount of generated traffic and the transport cost saving will increase by the amount of $[(T^* - T_1) \times (C_1 - C_2)]$. It is fair to say that cost reduction and generated traffic accounted in

HDM4 are the direct benefit on society especially road users. However, the cost may become a surplus cost if the traffic stays at the same rate.

The primary benefit in road investment is achieved when the total transport cost to be paid by society is low (Kerali et al., 2000). Therefore, the reduction in transport costs may occur if the road user costs component is reduced. For example, lower road roughness, shorter trip distance, faster speeds, reduced chance of impassability, reduced traffic problems, reduced vehicle operating costs, changes in road maintenance costs, changes in accident rates, increased travel, change in the value of goods moved and other environmental effects may reduce the road user costs which may result in the reduction of the total transport cost.

The evaluation of benefit in the economic analysis of HDM-4 is based on the Demand Curve theory which relates to traffic generation. On the other hand, the evaluation of benefit in the economic analysis of iRAP used the accident cost generation based on the Rule-of-thumb approach which has been derived from Human Capital and Willingness-to-pay estimation methods (McMahon and Dahdah, 2008).

Based on Jacobs (1995), the main components of the Human Capital approach are the costs that are due to a loss of current resources and also the costs that are due to a loss of future output. The iRAP approach in estimating benefit through accident cost may overly be priced as it also considers future output which may not accurately be reflected in the transport cost. However, it is believed that this approach is the most suitable to estimate the loss of the individual involved, the society and also the nation with regards to road safety. It is because the economic analysis in iRAP aims to maximise the national output and fulfil social welfare. It is suggested that the same approach to be used in any road safety investment appraisal model.

2.5 Relationship Between iRAP Star Rating and Road Standard

McInerney and Fletcher (2013) have presented that there is a relationship between the iRAP Star Rating and accident cost per vehicle kilometre travelled (VKT) based on a study in Queensland, Australia. From the study, it is suggested that an accident cost halved can be achieved by each Star Rating improvement. The result of the study is shown in **Figure 2.4**.

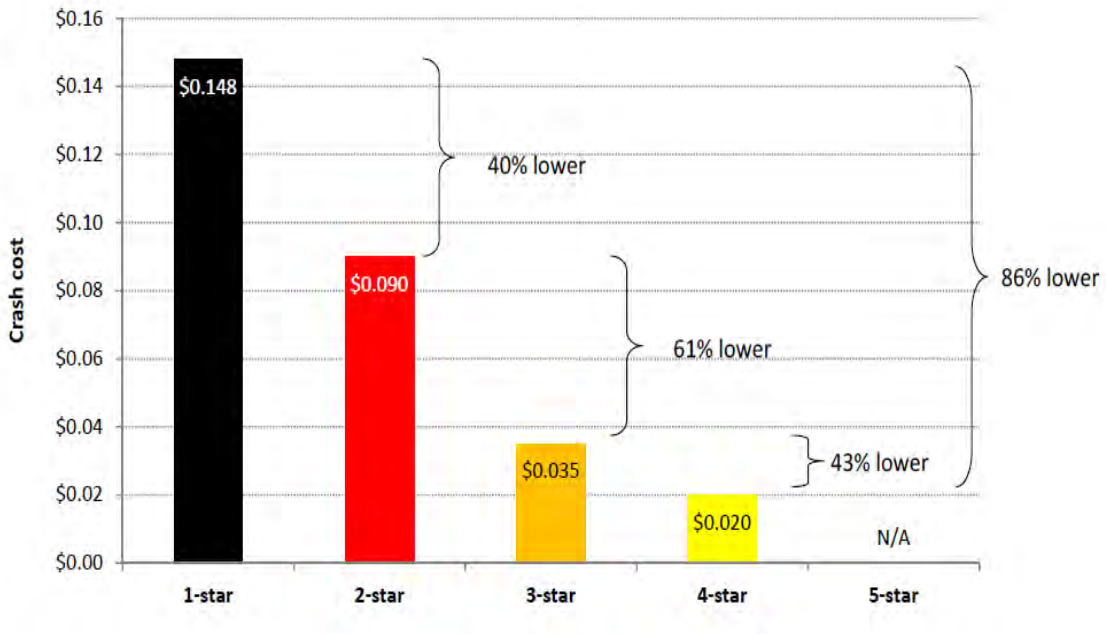


Figure 2.4 Accident cost halved for each Star Rating improvement

(Source: McInerney and Fletcher, 2013)

By overlaying the graphs in **Figure 2.2** (Odoki and Kerali, 2000)and **Figure 2.4** (McInerney and Fletcher, 2013), the fundamental idea of integrating the road safety and road asset management appraisal model can be explored further. We can assume each Star Rating from 1 to 5 respectively represents the road condition of Very Poor, Poor, Bad, Good and Very Good. The proposed alternative graph is shown in **Figure 2.5**.

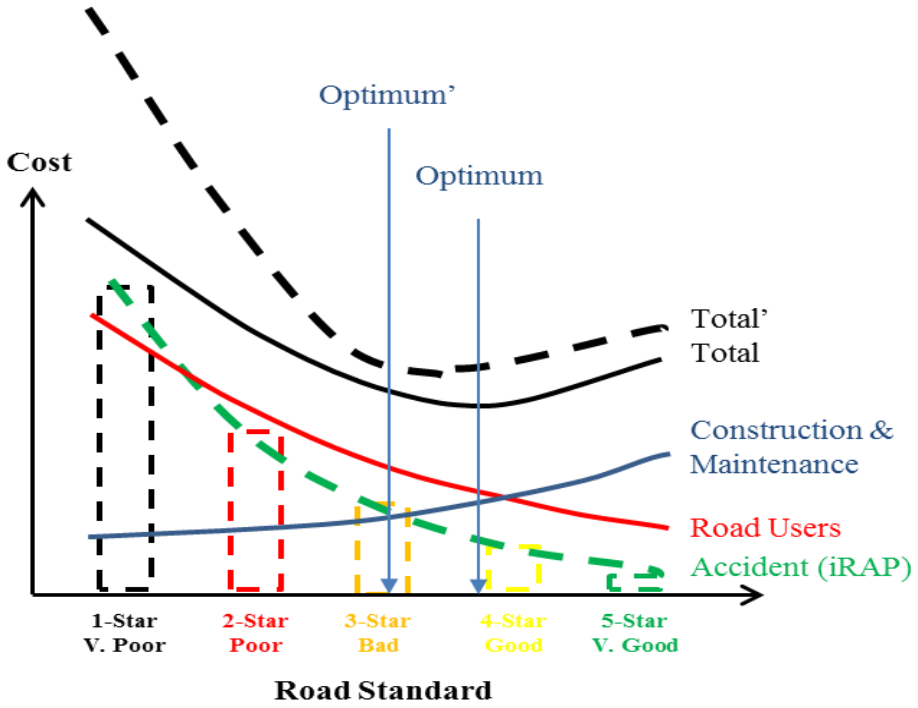


Figure 2.5 The proposed graph of road safety and road management integration

(Adapted and combined from Odoki and Kerali (2000) and McInerney and Fletcher (2013))

In general ratio, the green line (accident cost) in **Figure 2.5** may suggest that the accident cost is very high if the Star Rating or road standard is very low. This cost will reduce almost half for each Star Rating improvement. Additionally, we may look into the accident cost approach in a different way. As road accidents may become a source of disturbance in traffic, they may create frictions in the traffic stream, reduce traffic flow and increase vehicle operating cost (VOC) thus will increase road users cost (RUC). Therefore, it may be suggested that the accident cost that needs to be considered is the one related to road users effect (RUE) components, contributed by the Human Capital and Willingness-to-pay method as concluded by Jacobs (1995) or even McMahon and Dahdah (2008).

2.6 Deterioration Model and Concept of Life-Cycle Analysis

The life-cycle model of road asset as imposed in HDM4 is highly dependent on the pavement deterioration model. The pavement deterioration model used in HDM4 is well advanced. The application of maintenance standard on pavement structure will directly affect the performance throughout its life-cycle. To preserve the structural integrity of pavement, timely maintenance works under the required standard need to be carried out. **Figure 2.6** shows the concept of life-cycle analysis implemented in HDM4 for predicted pavement performance.

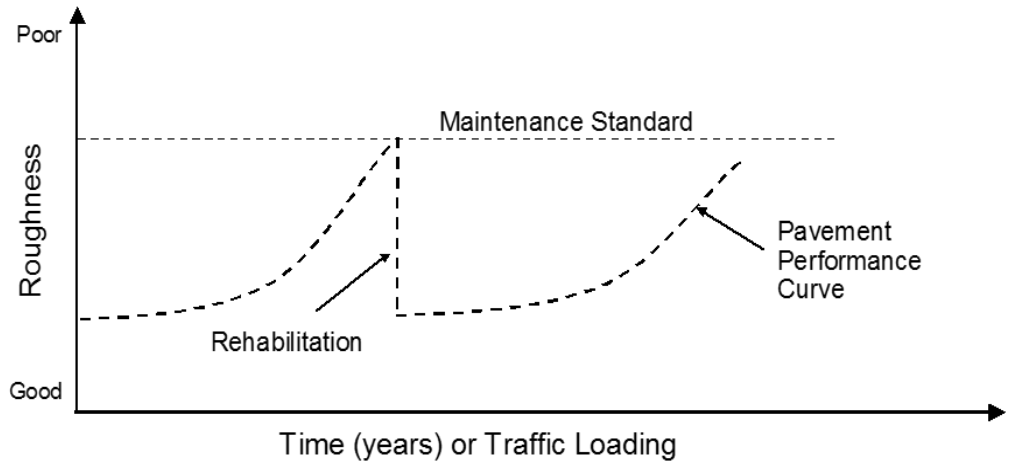


Figure 2.6 Concept of life-cycle analysis based on pavement deterioration model

(Source: Odoki and Kerali, 2000)

Similarly, the road safety appraisal model has to consider the life-cycle cost concept in its model as part of total asset management. Currently, the iRAP methodology adopted a simple life-cycle analysis based on the treatment life of a countermeasure (iRAP, 2014a). The iRAP methodology may seem to be advanced in providing road safety rating. However, its

methodology lacks treatment effects which are referred to as Road Works Effects or Maintenance Effects in road asset management.

According to iRAP (2019b), the list of treatments in the iRAP Road Safety Toolkit has nearly 50 types of countermeasures. The life-cycle analysis for these countermeasures will be more complicated in term of cost, treatment life and effectiveness. Information on treatment activities, treatment classification, treatment standard, treatment effects and treatment cost must be improved to a suitable standard. This will help in developing a better long-term life-cycle analysis of each treatment. Therefore, there is a need to develop the life-cycle model of road safety countermeasures.

2.7 Integration of Road Asset Management and Road Safety Model

The usage coverage of the road safety investment appraisal model such as iRAP is still very low compare with other road asset investment appraisal tools such as HDM-4. By integrating road safety and road asset management models, it may offer a wider outcome by considering road maintenance programmes that may contribute to road safety enhancement.

Li and Has (1998) have conducted a broad review to incorporate road safety into road asset management from the pavement engineering perspective. In their study, they have developed a general framework for analysing road accidents. The framework has indicated that inappropriate road geometric design and poor pavement surface conditions are the contributing factors of road accident related to the road environment. Based on this framework, it has been suggested that there is a significant relationship between pavement condition and road accident. This relationship has proven that road safety may be incorporated in the road asset management model as it is commonly associated with pavement condition.

Several studies have discussed the impacts of pavement properties, such as skid resistance and roughness on traffic accidents with relation to vehicle speed, weather conditions and visibility (Tighe et al., 2000). It was highlighted that regression analysis of road accident in Jordan in terms of the International Roughness Index (IRI) and Present Serviceability Rating (PSR) shown a significant relationship. Even though several studies have investigated the relationship between road condition and road safety, none of these studies has presented the dynamic change of road safety level in terms of road deterioration.

Mahoney et al. (2006) have reported the potential of incorporating road safety into maintenance activities. They have stressed how pavement surface properties such as friction, surface texture, roughness, distress and properties of paving materials affecting accident rate, especially in adverse weather conditions. Despite the growing interest in this topic, not many studies have been done related to the actual integration of road asset management and road safety model (Mahoney et al., 2006). However, Mahoney et al. (2006) have discovered that several good practices were incorporated road safety into resurfacing and restoration projects by many state Department of Transportation.

Tighe et al. (2000) and Mahoney et al. (2006) however supported the view that other road maintenance related to pavement surfaces such as geometric design or cross-section features, road marking, signing, and visibility of pavements contribute to road safety enhancement. Tighe et al. (2000) have highlighted a study that has investigated the road geometric elements such as lane width, shoulder clearance and other related road geometric design parameters in terms of road safety. It was concluded that improvement of road geometric design may significantly reduce road accident. Therefore, it is suggested that a further study on this area should be carried out as part of the integration.

Road investment appraisal is carried out to assess the benefits of a proposed roadworks scheme either for development or for maintenance. It is used as a decision-making process to evaluate the most appropriate return among investment options. This process will help the decision-maker to justify their decision based on available resources and future benefits that should be earned from the scheme. The criteria that are normally considered in a road investment appraisal consist of financial, economic, social, technical, and environmental issues.

The fundamental concept to optimise the decision-making process bears in life-cycle costing management. Considering the road asset management cycle, a life-cycle approach is used to assess the current condition of road assets and the future impact of any decision throughout the life cycle of the assets. For example, an initially constructed road section will experience deterioration due to traffic loading and environmental effects. Vice versa, the road condition may also improve with the implementation of appropriate maintenance.

It is necessary to model simulation on various effects of an event to the road condition to reflect its deterioration or improvement throughout the life-cycle analysis period. The road condition simulation can also be associated with cost estimation to monetise the effects as an economic analysis. This will enable the decision-maker to evaluate the long-term characteristics in terms of technical and economic aspects of the investment options.

Figure 2.7 shows a simplified life-cycle model that represents the flow of road life-cycle analysis from the construction phase to the maintenance phase as adapted from Robinson (2008). This model shows that after the construction phase ends, the road assets will be managed in the maintenance phase where the assets will start to deteriorate due to several factors such as traffic loading, environmental weathering and inadequate drainage effects. Hence, the assets will require maintenance to withstand the deterioration throughout their life cycle by increasing the condition of the assets.

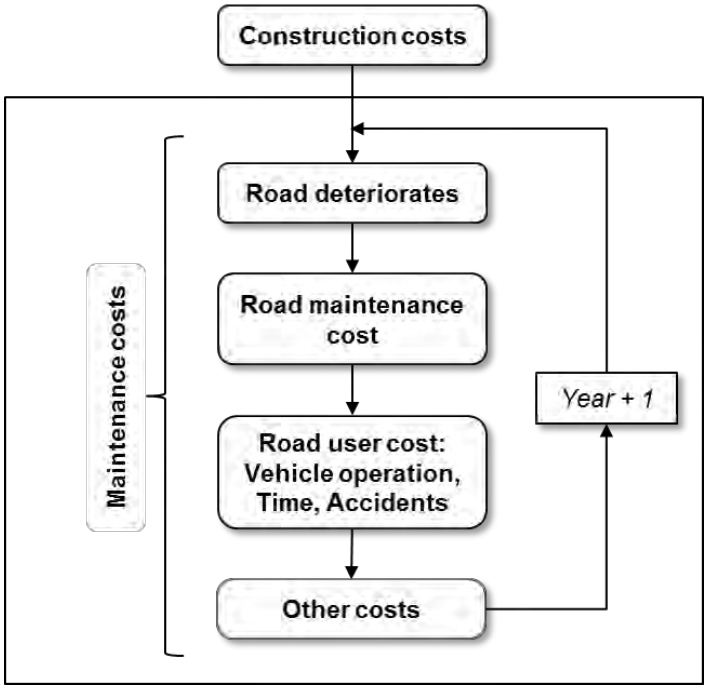


Figure 2.7 Simplified model of road asset life-cycle analysis

(Adapted from Robinson, 2008)

2.8 Conclusive Comparison of Road Management and Road Safety Model

Table 2.4 shows the basic comparison between road management and road safety model as a common road investment appraisal model. This comparison is presented in terms of five major aspects as follows:

i. Inventory Data;

ii. Intervention Level;

iii. Treatment Options;

iv. Economic Analysis;

v. Prioritisation

Table 2.4 Basic comparison between road management and road safety model

Contents / Input	Road Asset Management	Road Safety Management
Inventory Data	*Basic data* • Admin area • Geometric *Sensitive data* • Pavement data • Traffic data • Other (Climate etc)	*Basic data* • Admin area • Pavement data • Traffic data • Other (Climate etc) *Sensitive data* • Geometric (Road Attribute)
Intervention Level	• Defects • Roughness index • Traffic volume	• Safety level – Based on Star Rating Score (SRS)
Treatment Options	• Maintenance • Improvement • Development	• 74 countermeasures
Economic Analysis	• NPV/Cost Ratio	• B/C Ratio
Prioritisation	• Alternatives vs Without Project	• B/C Ratio Ranking
References:	*1. Kerali et al. (2000)* *2. Morosiuk et al. (2004)* *3. Odoki and Kerali (2000)* *4. Robinson (2008)*	*1. iRAP (2014a)* *2. iRAP (2019a)* *3. iRAP (2019b)*

Table 2.4 shows that the inventory data in both road asset management and road safety models have almost similar parameters. However, they differ in the aspects of intervention level, treatment options, economic analysis, and prioritisation method. Therefore, it can be concluded that the gap to integrate road management and safety model is considerably very wide. This is probably the reason why there are not many researchers who are interested to tackle the integration issue even though it may offer lots of opportunities. It is suggested that this research will look into the methodology on how to integrate both models in terms of these aspects.

2.9 Conclusion

This chapter has presented the critical literature review related to road management and road safety model that has been carried out throughout the research. The gap to integrate road management and road safety model is considerably very wide. Therefore, it may offer lots of opportunities to be explored.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The overall aim of this research is to integrate the road safety management and road asset management model using a parallel road investment appraisal model. Currently, the existing road investment appraisal models essentially consider either maintenance or safety in the assessment. Even the Highway Development and Management Tools (HDM-4), the most advanced road investment appraisal model does not fully consider road safety issues in the analysis. Conversely, the available road safety models lack life cycle analysis in their assessments. Therefore, the integration of both road safety and road management models would enable a feasible assessment of engineering and economic aspects of road safety and road management to be carried out concurrently.

This research focuses on the integration of both models in terms of their differences in the aspects of intervention level, treatment options, economic analysis, and prioritisation method. As highlighted in **Chapter 2**, various studies have evaluated the effects of road maintenance on road safety in terms of accident risks, accident prediction and accident reduction. This research will look into the overall effects of roadworks on road safety and their relationship with road conditions. Studying the effects of roadworks on road safety and road condition will help to enhance the existing road investment appraisal models.

Therefore, this chapter will discuss the overall methodology used to achieve the aim and objectives of this research. It is divided into six sections including this introduction. The

following section will explain the overall approach of this research. In the third section, the research design will be described concisely as the justification of the approaches used in the research. The theoretical framework and the method of the analysis will be explained in subsection 3.4. Data management and data gathering issues related to this research will be thereafter discussed followed by the conclusion of this chapter.

The overall methodology has been divided into four stages to answer four different research questions. As the research questions represent four different models or objectives, they will be further explained in their respective model development chapters such as **Chapter 5** (Modelling Road Safety Degradation), **Chapter 6** (Modelling Countermeasure Effects) and the analysis chapter of **Chapter 9** (The Ideal Integration Model) and **Chapter 10** (Proof-of-Concept Prototype for Integrated Model). The methodology has to be presented in such a way because the scope of this research has been broadened to develop a full working model that consists of several newly developed submodels.

3.2 Overall Approach

There are some common characteristics in the currently available road safety management tools. These models, which have been implemented in countries with the safest road networks, could perform analyses for road safety investment such as managing the information, setting policies, diagnosing the risk and problem, proposing the countermeasures, analysing the economic factor, planning the investment, and evaluating the outcome (PIARC, 2019). However, in practice, these models are used for separate investment appraisals from those for road management. Considering that the investment appraisal model in road management appears to be far more advanced, it is essential to compare both models to assess their gap and develop as well as integrate them for future enhancement of both models.

In general, the practice of both models is not fully integrated due to the following issues (Bennett and Greenwood, 2003):

i. Road safety has traditionally been excluded from many road investment models due to its complexity and uncertainty;
ii. There is a substantial limitation of transferring and sharing of information between developing and developed countries due to the different features of road conditions and traffic characteristics;
iii. There is a lack of empirical data to support the harmonisation of both models where the variables and analysis methods between models are not compatible with each other.

This research will propose a methodology to integrate both road safety and road management models in a parallel fashion. The integration will address all three issues that have been highlighted previously. In other words, the integration may provide a harmonised model between road safety and road management that considers different features of road conditions and traffic characteristics in both developing and developed countries. The integrated model will provide a platform for total road asset management that considers the life cycle of road safety aspects together with the road maintenance aspects.

To achieve this, it is needed to understand the relative interaction between road management and road safety concerning roadworks. In the broader context of this research, roadworks are referred to as road construction and maintenance works which are normally associated with condition improvement while countermeasures are referred to as roadworks which are normally associated with road safety improvement. Indicators related to road condition and road safety will be used to analyse the effects of road maintenance works and road safety countermeasures.

In general, it will be reasonable to assume that the implementation of any roadworks will positively affect the road condition and road safety level. In contrast, road deterioration will negatively affect road conditions and road safety levels. In the course of these events, certain road attributes will be affected by changes. The effect of changes in road attributes due to road deterioration and road works in terms of road condition and road safety level may be illustrated in **Figure 3.1**.

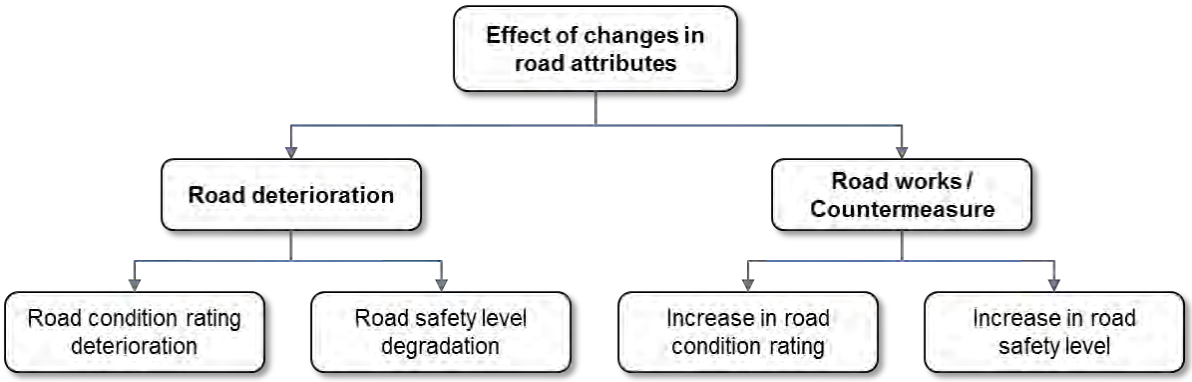


Figure 3.1 Effects of changes in road attributes

The situations that are illustrated in **Figure 3.1** will only occur when there are any changes in road attributes. However, the road attributes may not necessarily change over time when subjected to deterioration or roadworks. For example, a pavement surface, which is subject to road deterioration and roadworks, may change over time. Conversely, road deterioration that happens over time does not give any influence on road geometry. Considering the effects of roadworks, road geometry, as another example, may not change due to the effects of Routine or Periodic Maintenance. On the other hand, Improvement Works may change road geometry as they affect roadworks (Morosiuk et al., 2004). The matrix in **Table 3.1** shows the parameters which are directly affected by a different type of roadworks.

Table 3.1 Effect of roadworks on pavement parameters

Pavement Parameters	Routine Maintenance	Periodic Maintenance	Improvement
Safety	D	D	D
Condition	D	D	D
Structure	I	D	D
Geometry	N	N	D

D: Directly affected I: Indirectly affected N: Not affected

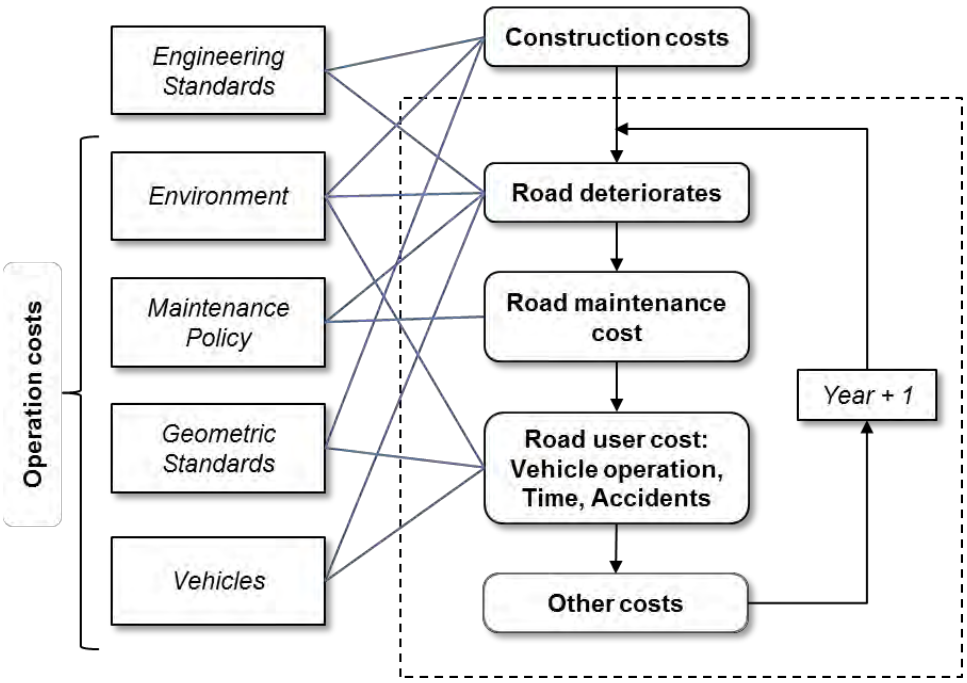


Figure 3.2 The annual cycle of cost and road deterioration

(Source: Robinson et al., 1998)

Robinson et al. (1998) have suggested that the annual cycle of cost and road deterioration is as shown in **Figure 3.2**. This figure explains the relationship of total transport cost change over time. The annual cycle is explained by the effect of road deterioration which will increase the

need for road maintenance. Consequently, as road condition becomes worse, traffic delays will subsequently increase travel time and accident risk which will affect the vehicle operating cost. All these costs are indirectly affected by the road engineering standards, the environment, the maintenance standards and the type of vehicles.

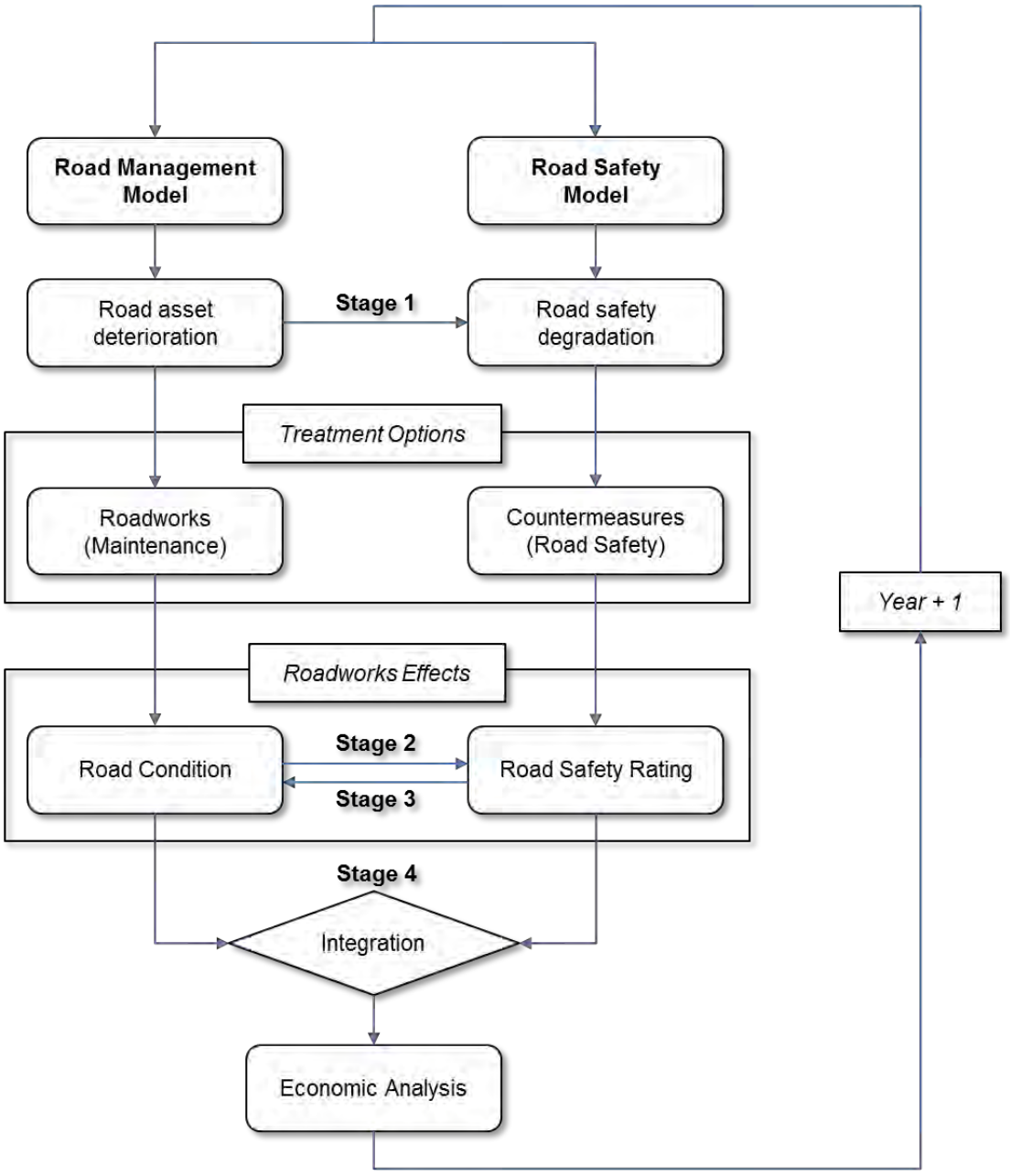


Figure 3.3 Overall approach to integrate road management and road safety model

A similar approach may be emulated to investigate the annual cycle of road safety degradation cost due to road deterioration. This will be the first step towards integrating both road asset management and road safety models. Therefore, **Figure 3.3** is proposed to emulate the annual cycle of road asset and road safety.

Figure 3.3 shows the overall approach to incorporate road safety into the established road management model as suggested by Robinson et al. (1998). The integration will require the harmonisation of certain parameters between both models to ensure that the change of attributes for each parameter over time can be assessed concurrently. As highlighted before, both models differ in four main aspects namely intervention level, treatment options, economic analysis, and prioritisation method. Therefore, the harmonisation of these aspects will be assessed through the analysis that will be carried out in four stages.

By harmonising the effects of road deterioration and roadworks on road condition and road safety levels, the life cycle of road assets may be assessed concurrently in consensus as an integrated model. As the first step, it is suggested that this approach may be started with the development of a road safety degradation model.

Road safety degradation is the process by which the safety level of a road asset depreciates under the combined effects of traffic loading and environmental conditions. At present, there is a lack of theoretical and empirical evidence related to this process, as it has never been studied by any researcher. This step will establish a methodology to project road safety levels due to road deterioration.

The treatment options will be generated based on the existing road management and road safety appraisal model. The available treatment options will be analysed to assess their effects on both road conditions and road safety levels. The assessment of road condition and road safety levels will be affected by an integration mechanism which may be considered as another contribution

to the body of knowledge. To complete this approach, an economic assessment will be carried out to analyse the available implementation strategies.

3.3 Justification of Research Design

The five characteristics of road investment appraisal that need to be considered in the proposed integration model are as follows:

i. Inventory data
ii. Intervention level
iii. Treatment options
iv. Prioritisation
v. Economic analysis

The approach of this research is based on the pavement life-cycle analytical framework. This analytical framework has been chosen because it considers the whole life cycle of road assets. The existing road management and road safety models use common inventory data that may complement each other. This is because both models require information quality levels that fulfil the necessary applications and data collections suitable for their purpose (Robinson et al., 1998). To fulfil the need of each model, the treatment options will be generated by the available model respectively.

The methodology to assess road safety level has been established by several existing models. These methodologies can be utilised to develop road safety degradation. The road safety degradation model will need to be synchronised with the pavement deterioration model to study the relationship between road safety degradation concerning road deterioration. The effects of roadworks and road safety countermeasures will be analysed to identify the priority of the

works based on available implementation strategies and their objectives. The economic analysis will be carried out to assess the financial aspect of the integrated model.

In general, the integrated model will perform a parallel assessment of road asset and road safety management. An integration mechanism will be introduced for the interaction of the road management model with the road safety model. The overall technical and economic assessment for the whole model will be carried out using the established road management model alongside the road safety assessment in a separate model.

3.4 Method of Analysis

It was felt that to achieve the above, it is essential to understand the relationship between road safety level and pavement deterioration model. **Figure 3.4** shows the timeline that explains the theoretical prediction of road safety level relative to road condition due to road deterioration and various roadwork effects.



Figure 3.4 Theoretical prediction of road safety rating and road condition over time due to road deterioration and roadwork effects

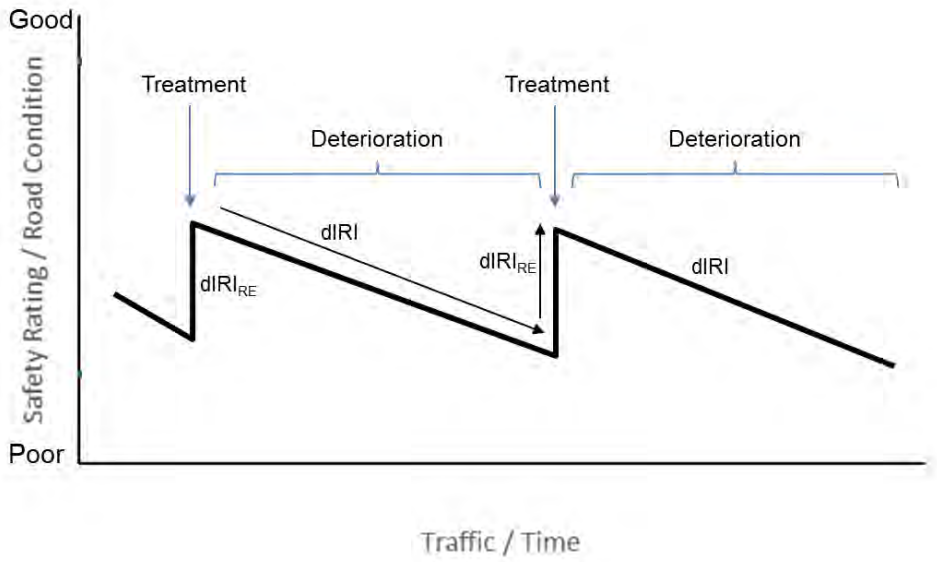


Figure 3.5 Predicting future road condition

The theoretical diagram in **Figure 3.4** can be simplified as **Figure 3.5** to describe how to predict the future road condition. From Odoki and Kerali (2000), the prediction of future road condition can be derived from **Eq. 3.1** as below:

$$IRI_{n+1} = IRI_n + dIRI + dIRI_{RE} \quad \textbf{(3.1)}$$

where,

IRI_n = Roughness at the start of the analysis;

IRI_{n+1} = Roughness at the end of the analysis;

$dIRI$ = Roughness increment due to deterioration;

$dIRI_{RE}$ = Roughness decrement due to roadwork effects.

Similarly, future effects of road safety level can be written with the following equation:

$$RSR_{n+1} = RSR_n + dRSR + dRSR_{CE} \quad \textbf{(3.2)}$$

where,

RSR_n = Road safety rating at the start of the analysis;

RSR_{n+1} = Road safety rating at the end of the analysis;

$dRSR$ = Road safety rating decrement due to deterioration;

$dRSR_{CE}$ = Road safety rating increment due to countermeasure effects.

Furthermore, to answer the research problem, there are four sets of research questions that need to be answered as summarised in **Table 3.2**. In general, the research questions are set to analyse the relative effects and changes in road safety level and road condition due to road deterioration and roadwork effects throughout the analysis period. These research questions are assigned to the respective stages of the analysis as shown in **Figure 3.3**. The instruments and data analysis methods used for each stage are summarised in **Table 3.2**.

Table 3.2 The instruments and data analysis methodologies used in answering the research questions

Stage	Research Question	Instrument	Data Analysis
Stage 1	**RQ1:** What are the effects of road deterioration on road safety level?	Road Safety Rating (RSR)	Sensitivity Analysis
Stage 2	**RQ2:** What are the effects of road maintenance works on road safety level?	Simulation (Road Safety Rating)	Incremental Model
Stage 3	**RQ3:** What are the effects of road safety countermeasures on road condition?	Simulation (Roughness Index)	Incremental Model
Stage 4	**RQ4:** What are the effects of a different roadworks implementation strategy on the road condition and road safety level?	Simulation (Road Safety Rating and Roughness Index)	Incremental Model and Economic Analysis

In the **first stage** of the analysis, a road safety degradation model will be established. As there are not enough empirical data to establish a road safety degradation model, a probabilistic model will be used based on the pavement deterioration model and road safety analysis. The probabilistic model will be applied to predict the probability of an outcome instead of predicting a set of the specific outcomes of an event if a deterministic model were used. According to Robinson (1998), a probabilistic model is preferred over a deterministic model for the assessment of overall network investment needs.

In order to develop the road safety degradation model, probable changes to road safety levels will be analysed to predict the probability of any effect of degradation on road safety resulted from road deterioration. A sensitivity analysis will be carried out to determine the contributing factors and the scale of deterioration that affects the road safety level. The road safety degradation model will be established based on the result of the sensitivity analysis.

In the **second stage**, the analysis will be related to the effect of roadworks or countermeasures on the road safety level. These roadworks will be categorised based on their effect on road safety level changes. The changes will be calculated based on the formula in **Eq. 3.2**. An incremental model will be used to predict the change in condition from the beginning of the analysis as a function of independent variables. This model is chosen over an absolute model because the absolute model predicts the future condition which is limited to the conditions that the model is developed for.

Similarly, in the **third stage**, the effect of road safety countermeasures on road condition will be analysed using the available road appraisal. Finally, the effects of a different roadworks implementation strategy on road condition and road safety level will be analysed in the **fourth stage**. At the end of the research, it is envisaged that the analysis will be able to identify the appropriate strategy to optimise the benefits of road safety and road maintenance works.

3.5 Data Collection Method

Data collection is a major concern for this research. It is because the data collection related to road assets management studies are often very costly as they may require high precision equipment and their analyses of raw data may be time-consuming. Some of the options for data collection in this research are as follow:

i. To use primary data that need to be collected by the researcher using high-speed collection methods with the cooperation and financial support by the relevant road authorities;
ii. To use secondary data that has been gathered from other individuals or groups for other purposes or research projects. This data may be available from the relevant road authorities, reports and studies; or
iii. To use artificial or simulated data which can be produced without direct measurement based on a required standard. This data can be created to meet the standard that fulfils the existing road asset management data collection requirements.

All three options will be explored in this research. However, the second and third options are more realistic for the execution of this research. Even though cost and time are constraints, the decision to opt for the two options will be made on the basis that they offer a better road network coverage and relatively will represent the overall network conditions. Furthermore, this simulation-based research will be more effective if the variables can be controlled and used to provide a significant number of scenarios to be tested.

The main challenge of the data collection for this research is to gather data associated with two independent exercises from road maintenance and road safety data collections. These exercises are performed for different purposes in mostly two independent areas. A preliminary

assessment needs to be done to ensure that the selection of the secondary data is consistent, has comprehensive coverage and could complement each model.

To fulfil this requirement, synthetic data or artificial data is used as a supplement to the secondary data. This is to ensure that the data from both road maintenance and road safety models are synchronised and well prepared for the integration to take place. In this simulation-based research, the use of secondary data is more beneficial and effective because the variables can be controlled and manipulated to provide significant numbers of scenarios.

For this research, a case study will be conducted in Malaysia. Malaysia has been selected for the case study because it is categorised as a developing country as well as a middle-income country. Road transport is the main transportation mode for goods and passenger transport in Malaysia with road infrastructure networks are widely covered and mostly matured. In general, the road standard in this country is considered high which covers a various range of road condition with significant road maintenance fund. In term of road safety, it has high road traffic usage which recorded a high annual accident rate.

3.6 Conclusion

This chapter described the methodology used in this research to develop integrated road safety and road management as a total road appraisal model. The overall approach is based on a parallel analysis of road condition and road safety level to determine the effect of changes in road attributes due to road deterioration and roadworks. The pavement life-cycle analytical framework has been adapted to develop the basis of the road safety and road management parallel analysis.

Four research questions have been identified for this research. A sensitivity analysis will be carried out to develop a road safety degradation model based on road condition and an

established pavement deterioration model. The effect of road deterioration and roadworks will be analysed using an incremental model to establish the relative behaviour between road safety and road maintenance. Finally, an economic analysis will be carried out to identify the optimum implementation strategy for integrated road management.

Data management issues especially related to the data collection method should also be considered. It is suggested that a road network in Malaysia will be selected to test the concepts of this research. The selected network will represent a range of different road conditions with high traffic volumes and significant numbers of road traffic accidents.

To conclude this methodology chapter, the methodology of this research can be found as below:

i. HOW the research is carried out – **Chapter 3**;

ii. WHERE the data is originated from – **Chapter 7 and 8**;

iii. WHAT data gathering techniques are used – **Chapter 8**;

iv. WHY particular methods and techniques to gather data were chosen – **Chapter 8**

CHAPTER 4

BASIC CONSIDERATIONS FOR MODEL DEVELOPMENT

4.1 Introduction

In this chapter, the road safety model will be examined with regards to its fundamental concepts, model components and its limitations. This will help to identify its commonalities and potential matching points to enable its integration with the road management model.

This chapter will first present the technical considerations that are based on the relationship of road deterioration and roadworks with road safety performance. This will be followed by a brief presentation of the International Road Assessment Programme (iRAP) and its Star Rating Score (SRS) as a road safety assessment tool that will be used to evaluate road safety performance. The selected road management model will also be presented as an introduction before it is used in this research.

Certain limitations have to be considered as there is quite a substantial gap between road management and the road safety model. To understand this, further investigation will be carried out on the iRAP's Star Rating Score to identify the influenced factors that control road safety performance. The life-cycle concept of road safety performance will be introduced in the final section of this chapter.

The submodels development of the Road Safety Degradation Model and the Countermeasure Effects Model will be presented in **Chapter 5** and **Chapter 6** respectively. **Chapter 4** has to be introduced before the actual submodel development chapters because it contains the methodology and consideration to assess the road safety aspects of both submodels later.

4.2 The Modelling Concept

4.2.1 Effects of Road Maintenance

There are several purposes for road maintenance. The main ones are as follows (Robinson et al., 1998):

i. reduce the rate of pavement deterioration;
ii. lower the vehicle operating costs;
iii. keep the road open;
iv. improve road safety and reduce road accident;
v. increase resilience to the environment.

Appropriate management activities are required to effectively and efficiently plan, execute and monitor the road maintenance programmes. All the above road maintenance purposes should be monitored and evaluated to assess the effectiveness of road management. Road management appraisal tools may assist as decision-support tools to carry out this task.

There are several road management appraisal tools widely used by road managers around the world. These tools mainly will assist in achieving the objectives of road management such as managing road deterioration, regulating vehicle operating cost, keeping roads open and protecting the environment (Archondo-Callao, 2009). However, these tools do not explicitly provide the required support for the road safety aspect of road management (Bennett & Greenwood, 2003).

Bennett & Greenwood (2003) have concluded that several issues related to road safety model exist within the existing road management appraisal models. There are limited studies that successfully linked accidents to geometric design parameters. The use of geometric parameters to represent uniform road sections or homogeneous road design between these studies has

proven that most accident prediction models are statistically inconsistent. The complexity and uncertainty of the accident have made the accident cost to be the main selection criterion for road safety in most road management appraisal models. However, this will not hinder the effort to link road safety performance concerning geometric parameters.

Figure 4.1 shows the taxonomy of the main factors that contribute to traffic accidents and injuries as presented by Elvik et al. (2009). In principle, the number of people killed or injured in road accidents is controlled by exposure, injury severity and accident rate. Road infrastructure contributes to the injury severity and accident rate factors which will be significant in lowering the risk of road accidents. Therefore, road maintenance works may increase the road safety level by eliminating or reducing the accident risk contributed by road infrastructure design.

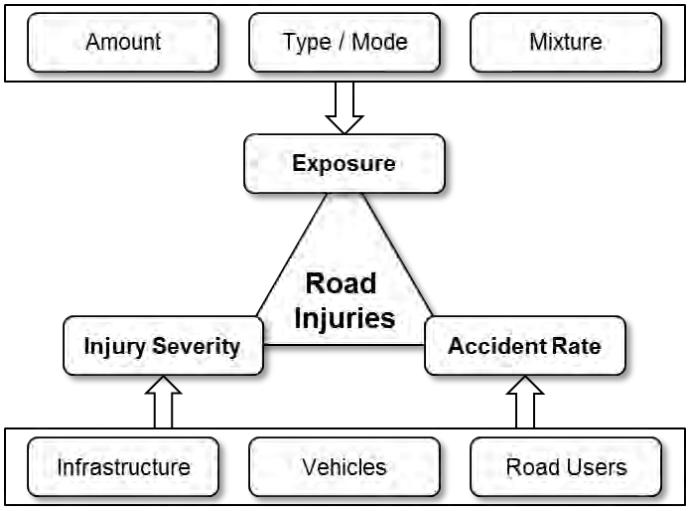


Figure 4.1 Taxonomy of the factors that influence road safety

(Source: Elvik et al., 2009)

4.2.2 The Modelling Approach

There are four basic road safety programme strategies for accident risk reduction namely single site or also known as blackspot treatment, mass action scheme, route action plan and area-wide scheme (Baguley, 1995). These strategies offer the opportunity to improve the road safety risk attributes contributed by a modification of road infrastructure in the following areas (Robinson et al., 1998 and Bennett & Greenwood, 2003):

i. Carriageway pavement and pedestrian footpath surfaces;
ii. Road markings and delineation;
iii. Road signages, street lightings and road furniture;
iv. Geometric and alignments enhancement.

One of the known characteristics of road infrastructure, it may experience deterioration over time. As some of the road attributes are subject to change over time, the state of road safety performance may depend on road deterioration and roadworks effect. **Figure 4.2** displays the relationship between road condition performance and road safety performance as the dependent variables (DV) relative to road deterioration and road works as the independent variables (IV).

In general, road assets may experience deterioration due to traffic loading and road environment effects. In principle, road deterioration will most likely cause the road safety level to decrease. To restore the road condition up to a certain standard, proper road maintenance works have to be carried out. Similarly, the road safety level can be increased by applying certain countermeasures. Indirectly, the implementation of road maintenance works may also increase the road safety level. The development of the road safety degradation model and the countermeasure effects will be discussed in details in **Chapter 5** and **Chapter 6** respectively.

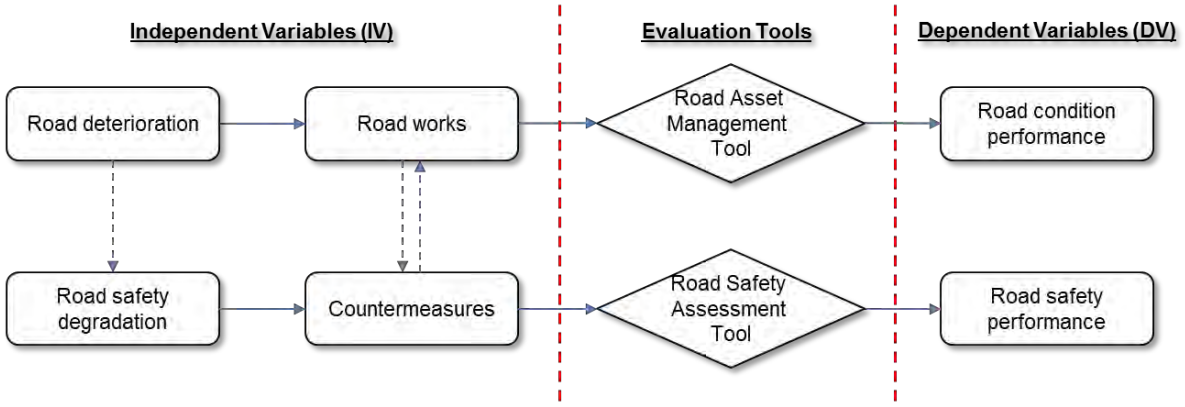


Figure 4.2 Relationship of road safety performance relative to road deterioration and road works

The above relationship shown in **Figure 4.2** may be evaluated using a road asset management tool and road safety assessment tool. These tools are required to evaluate the effects of changes in road attributes in terms of road condition and road safety performance. The evaluation may consider the road condition and road safety performance at any particular time from the design stage to the operational stage. The road safety assessment tools could be utilised to evaluate the existing condition of road safety, assess changes in road safety level affected by road deterioration and roadwork, and predict the future condition of road safety level including the condition projection as well as the projection during the design stage for a road safety audit.

4.3 Road Safety Assessment Tool: Star Rating Score (SRS)

For this research, the Star Rating Score (SRS) which has been introduced by the International Road Assessment Programme (iRAP) will be used as the road safety assessment tool. The following sections will describe the application of the Star Rating Score as a road safety assessment tool and will be followed by a brief introduction to the road asset management tool that will be used in this research.

The Star Rating Score (SRS) is a method of calculation, developed and supported by the International Road Assessment Programme (iRAP), to assess roads all over the world in terms of road safety performance. The aims of the Star Rating Score and the iRAP methodology is to significantly reduce road casualties by improving the safety of road infrastructures. Since the pilot studies in 2006, the iRAP activities have been extended to over 70 countries, with an estimated 500,000 kilometres of road have been assessed (iRAP, 2019a).

From the road assessment, images, and videos of the road, location data with a global positioning system (GPS) compliance and distance data are collected during road inspections. The information is recorded either using a high-speed road survey vehicle or manually. It is then coded to categorise the road attributes. In general, the recorded road attributes data consist of descriptive road attributes and other attributes that influence the likelihood and severity of road accident. The summary of the iRAP Road Attributes is listed in **Appendix 1**.

From the road attributes data, the Star Rating Score can be calculated as a measure of road safety performance. The Star Rating Score represents the relative risk of death and serious injury for an individual road user and can be calculated using the following equation (iRAP, 2013a 2013b, 2013c, 2014b):

$$SRS = \Sigma\ Crash\ Type\ Scores \quad \textbf{(4.1)}$$

$$= \Sigma\ [Likelihood \times Severity \times Operating\ speed \times External\ flow\ influence \times Median\ traversability] \quad \textbf{(4.2)}$$

where,

Likelihood : road attribute risk factors that account for the chance that a crash will be initiated;

Severity	:	road attribute risk factors that account for the severity of a crash;
Operating speed	:	factors that account for the degree to which risk changes with speed;
External flow influence	:	factors account for the degree to which a person's risk of being involved in a crash is a function of another person's use of the road;
Median traversability	:	factors account for the potential that an errant vehicle will cross a median. It only applies to vehicle occupants and motorcyclists run-off and head-on crashes.

From **Eq. 4.1** and **Eq. 4.2**, it may be seen that the Star Rating Score is calculated based on five road attribute risk factors. The risk factors, also known as the crash modification factors (CMF), are used in the iRAP Star Rating methodology to relate road attributes and crash rates. The crash modification factors (or in this research will be referred to as risk factors) are defined by the Crash Modification Factor Clearinghouse (CMFC) as a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site (CMFC, 2010).

The risk factors are associated with road attribute, road user types and crash types. The selection of the risk factors is based on extensive reference to available research and studies related to respective road attributes. The full list of the iRAP Road Attribute Risk Factors is available in their resources list on their website (www.irap.org). The diagram in **Appendix 2** may explain the application of the above Star Rating Score equations.

4.3.1 Road Deterioration Effects on Road Safety Performance

Figure 4.3 is adapted from the Star Rating Score equations diagram specific for vehicle occupants as provided in **Appendix 2**. This diagram shows how various road attributes contribute to the Star Rating Score. The Star Rating Score was developed from the risk assessment models of a series of crash initiation modes (iRAP, 2013b). The Crash Type Scores are calculated based on the crash initiation modes and their contributing factors that initiate road accidents. For example, vehicle occupants, the crash types that need to be considered are as follows:

i. run-off (driver-side): if the vehicle departs to the driver's side when there is no oncoming vehicle present;
ii. run-off (passenger-side): if the vehicle departs to the passenger's side when there is no oncoming vehicle present;
iii. head-on (loss of control): if the vehicle departs to the driver's side when there is an oncoming vehicle present;
iv. head-on (overtaking): if the vehicle performing overtaking manoeuvre when there is an oncoming vehicle present;
v. intersection: if the vehicle travelling in the same direction (rear-end) or performing a turning manoeuvre (side and frontal) when there is an oncoming vehicle present;
vi. property access: if the vehicle travelling in the same direction (rear-end) or performing a turning manoeuvre (side and frontal) when there is an oncoming vehicle present.

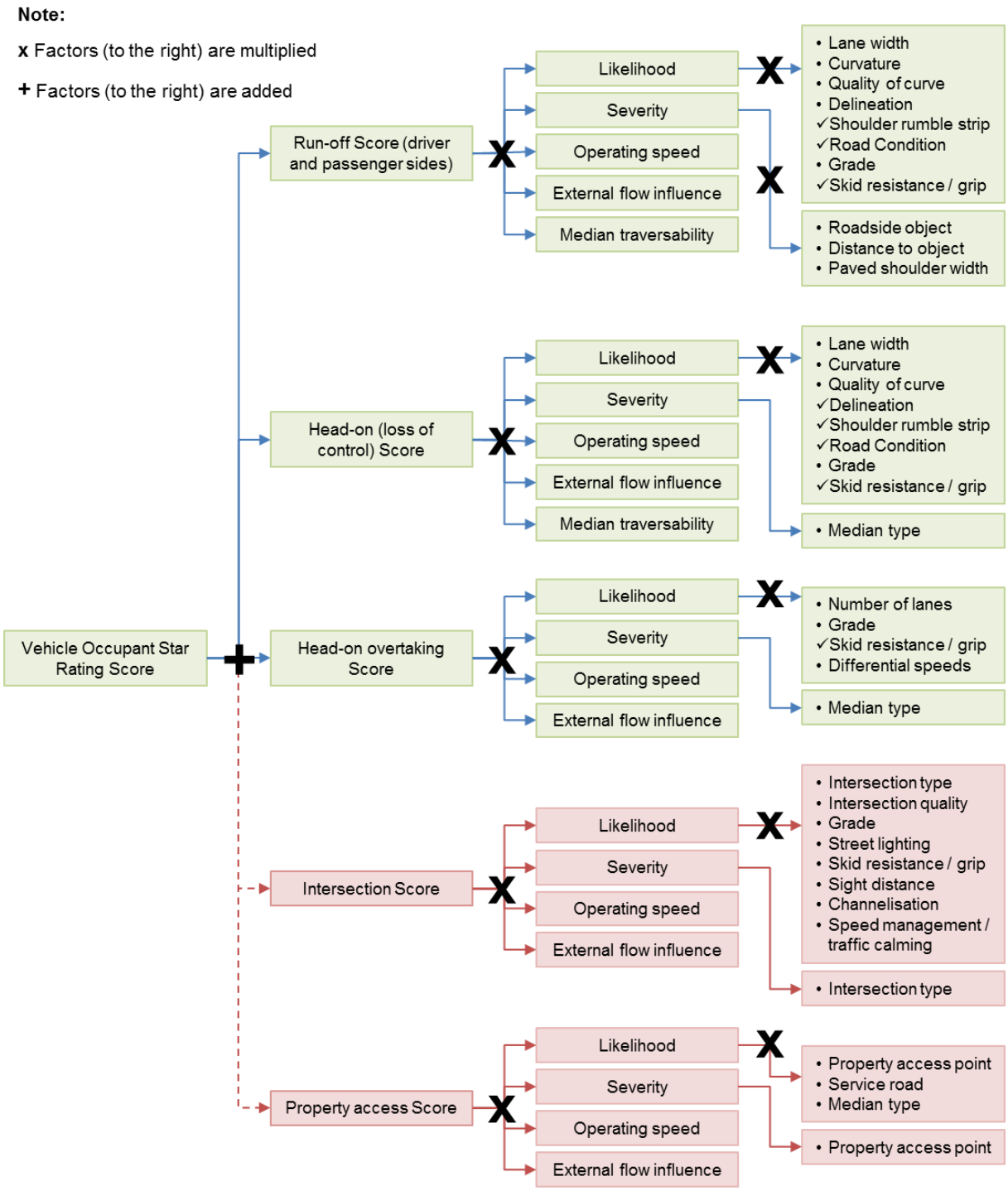


Figure 4.3 Vehicle occupant Star Rating Score equations diagram

(Adapted from iRAP, 2014)

For this research, it is assumed that the selected network considered in the model typically consists of one continuous road. This assumption is made typically because at the strategic or network level, a generalised analysis based on a continuous road stretch is adequate. Furthermore, the iRAP Star Rating Score may produce a similar score as a typical road section for the other road geometric formation. For example, a roundabout may produce a similar score as a typical road with poor quality and sharp curvature. With a similar concept, an intersection or a ramp that connects to a major road may be analysed as two separate typical road sections.

Therefore, the Intersection and Property Access crash types may be ignored. This will leave only the run-off and head-on crash types to be considered in the model as shown in **Figure 4.3**. This is in line with the needs of the typical information quality level (IQL) for a strategic level analysis which will require just a basic summary data of inventory. This basic level of required data is often referred to as IQL-III or IQL-IV which appropriate with the size of the network and suitable for the requirement of the network-level analysis (Robinson et al., 1998).

To assess the effects of road deterioration on road safety performance, a further examination needs to be done on the road attributes or road assets to identify their probable changes over time. For example, Lane Width and Curvature are dimensional properties that are relatively constant or will not deteriorate over time without roadworks. In contrast, some other road assets such as road pavement and road marking are relatively subjected to deterioration and will change over time.

4.3.2 Road Attributes Not to be Considered in the Model Development

From **Figure 4.3**, all the road attributes that contribute to each crash type scores and further contribute to the overall Star Rating Score may be easily identified. It has been decided that the Intersection and Property Access crash types are discarded from the equations. This will

leave the Intersection Type, Street Lighting, Sight Distance, Speed Management or Traffic Calming and Service Road are among the attributes that will not be considered in this model.

These road attributes are generally present at Intersection and Property Access Point and negligible at other sections of the road. It can be confirmed from the Star Rating Score calculation that the existence of Street Lighting and Speed Management or Traffic Calming on a straight road will not influence the Star Rating Score value. The Sight Distance, the Intersection Type and Service Road attributes may not influence the Star Rating Score because the drivers' view is confined within the carriageway. Therefore, all these road attributes which are related to the Intersection and Property Access crash types do not apply to the proposed model.

The road attributes which contribute to the rest of the crash type scores also need to be examined to determine their influence on road deterioration. It is easy to determine the road attributes that carry the dimensional properties such as Lane Width, Curvature, Quality of Curve, Grade and Paved Shoulder Width. These road attributes use dimensional values that are constant and will not change over time.

Similarly, road attributes that are associated with physical appearances such as a Roadside Object, Distance to an Object, Median Type, Differential Speeds Limit and Number of Lanes appear to be constant and will not change over time. Although certain Median Types arguably need a certain type of maintenance, they may need a long period to naturally deteriorate unless they are involved in an accident, which is also out of the consideration of this research. Therefore, all these road attributes related to dimensional properties and physical appearance are considered not influence by road deterioration.

The assumption to exclude the Intersection and Property Access score is considered appropriate as they involved only the Street Lighting attribute which is also subject to deterioration.

However, the deterioration of street lighting is often considered negligible. It is also often that street lighting is not directly modelled in most road asset management models.

4.3.3 Road Attributes to be Considered in the Model Development

From the above assumptions, this has left Delineation, Shoulder Rumble Strip, Centreline Rumble Strips, Road Condition and Skid Resistance/Grip are among the road attributes to be considered in this model. Delineation is a physical road attribute such as road marking, road signage and road furniture that helps drivers to recognise the driveable area within the carriageway ahead. Road marking contributes most of the Delineation attribute score along the route as it should be continuously present.

Shoulder and Centreline Rumble Strips are other types of road marking that provide additional safety effects using vehicle vibration if vehicle tires are driven on and in contact with them. In general, road marking has a life span of about two to five years depending on traffic and the quality of applications. Therefore, all these road attributes related to road marking should be considered in this model as they change over time and will be influenced by road deterioration.

Road Condition and Skid Resistance/Grip are related to pavement condition. Road Condition is often referred to as roughness which is associated with the condition of the road structure and road surface. Further explanation of road condition and roughness in the context of this research will be given in **Chapter 5**.

Skid Resistance/Grip is often referred to as the measure of the pavement surface to resist the skidding effects of vehicles based on the tyre contact. As they are the main components of road that are continuously subject to the road environment and traffic loading, Road Condition and Skid Resistance/Grip should be considered in this model as they change over time and will be

influenced by road deterioration. **Table 4.1** shows the list of road attributes based on their influence on road deterioration over a significant period.

From the brief examination, it has been identified that five road attributes are directly affected by road deterioration, namely Delineation, Shoulder Rumble Strip, Centreline Rumble Strip, Road Condition, and Skid Resistance/Grip. These road attributes, in general, have a relatively short life span and are confined within the carriageway. All these road attributes are continuously exposed to the environment and traffic loading.

Table 4.1 Influence of road attribute to road deterioration

Fluctuate	Constant	Not Applicable
a. Delineation	a. Lane width	a. Intersection type
b. Shoulder rumble strip	b. Curvature	b. Intersection quality
c. Centreline rumble strips	c. Quality of curve	c. Street lighting
d. Road Condition	d. Grade	d. Sight distance
e. Skid resistance / grip	e. Roadside object	e. Channelisation
	f. Distance to object	f. Speed management
	g. Paved shoulder width	g. Property access point
	h. Median type	h. Service road
	i. Street lighting	

(Adapted from iRAP, 2019b)

4.4 Road Asset Management Tool: Road Network Evaluation Tool (RONET)

The Road Network Evaluation Tools (RONET) is a decision support tool to evaluate the performance of road maintenance management policies. It has been developed by the World Bank to assist in monitoring the road network conditions, planning the implementation of the

maintenance programme and evaluating the road user costs. It can be utilised to assess the road network performance over time under different road maintenance strategies and to determine the maintenance budget for routine maintenance, periodic maintenance, and rehabilitation works (Archondo-Callao, 2009).

The model has been developed based on the fundamental principles adopted from the most advanced road management appraisal model, the Highway Development and Management (HDM-4) model. However, it uses a simplified road deterioration model derived from the HDM-4 and it simplifies the road user costs relationships. Although it has been simplified from HDM-4, it can perform a strategic economic analysis of a network similar to what can be done in HDM-4. The model comes with an evaluation tool with a simple interface that may not require an expert to run the model.

The components in the RONET comprise of the following evaluation modules:

i. Current Condition Assessment: to assess the existing road network condition and monitor the road network performance indicators;
ii. Performance Assessment: to evaluate the road network performance under different budget scenarios and forecast the future outcome to stakeholders;
iii. Road User Charges: to calculate the road user charges and revenue to match the needs of road maintenance.

4.4.1 Road Condition Classes

Each road will be classified into five road condition classes based on the type of road maintenance works required. The type of road maintenance works will generally indicate the condition of the road. Further explanation about the road maintenance works will be presented

in **Chapter 6**. The following are the road condition classes for paved roads as defined in RONET to indicate the network pavement condition:

i. Very Good: Roads in very good condition which require minimum maintenance works such as routine maintenance with no capital road works;
ii. Good: Roads in good condition which are mainly free of defects, require some minor maintenance works such as preventive treatment or surface dressing;
iii. Fair: Roads in fair condition which are roads with some defects and structural deficiencies, require some periodic maintenance such as resurfacing without the need to remove the existing pavement;
iv. Poor: Roads in poor condition which are roads with some major defects and structural deficiencies, require rehabilitation such as partial reconstruction or structural strengthening;
v. Very Poor: Roads in a very bad condition which are roads with largely major defects, require full reconstruction or new construction or upgrading.

Figure 4.4 shows the cracking progression model adopted in the RONET for bituminous pavement. The sigmoidal graph shows the growth of road defects to indicate the network condition over a period. Each of the condition depicted in this model may be presented in the RONET default road condition classes in terms of roughness as the average roughness values shown in **Table 4.2**.

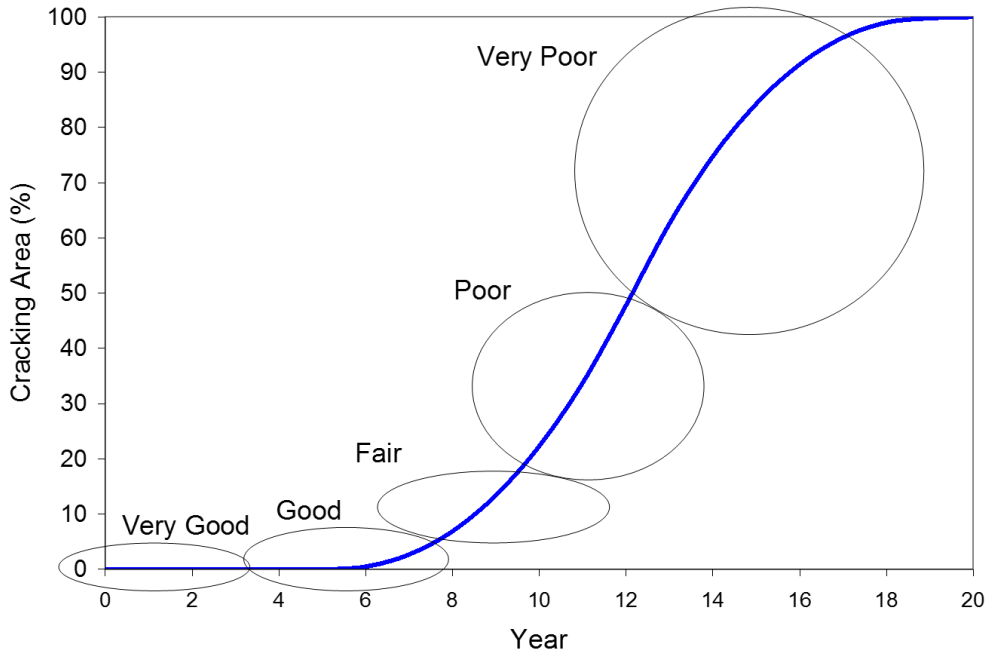


Figure 4.4 Cracking progression model adopted in RONET

(Source: Archondo-Callao, 2009)

Table 4.2 Average roughness value of each road condition class for asphaltic pavement

Condition Category	Roughness (IRI m/km)		
	Minimum	**Maximum**	**Average**
Very Good	1.0	2.5	2.0
Good	2.5	3.5	3.0
Fair	3.5	5.5	4.5
Poor	5.5	10.5	8.0
Very Poor	10.5	16.0	12.0

(Source: After Archondo-Callao, 2009)

4.5 Consideration and Limitation of the Model Integration

There are some basic considerations and limitations in the integration model that have to be considered in this research. They need to be acknowledged to ensure all the conditions that have been set for this research will be considered in future exercise. Following the examination of the influential road attributes to road deterioration, there are other considerations appropriate for this research in terms of countermeasures standard, operating speed, and the overall limitations.

4.5.1 Countermeasures Standard

The International Road Assessment Programme (iRAP) administration has provided the Road Safety Toolkit as a reference to information on the causes and prevention of road crashes that cause death and injury. The toolkit has been developed in collaboration with experts and other organisations with an interest in road safety such as the World Bank Global Road Safety Facility. Together with the information on the causes and prevention of road crashes, the toolkit can be used as a quick reference to other key information such as the generic cost of treatment, life span, and their effectiveness.

However, life-cycle analysis of road safety performance seems to be as complex as, if not more complex than, the pavement life-cycle analysis. As the level of road deterioration increases over time, the level of road safety performance may also decrease, hence, which in turn increases the need for road maintenance and upgrading. The iRAP's Road Safety Toolkit has very limited information regarding the life-cycle of a countermeasure to consider this complexity. Therefore, the life-cycle analysis of countermeasures' safety performance needs to be further developed.

In general, the life span for each treatment or road asset element as provided by the iRAP's toolkit may be categorised into four generic life span as shown in **Table 4.3**. The life-cycle of road safety performance is influenced by the life spans of the treatments. The generic life span of the treatments could form the basis for the establishment of life-cycle analysis for road safety performance. The details of the full toolkit can be referred to at http://toolkit.irap.org (iRAP, 2019b).

Table 4.3 Treatment life span

Life span	Term	Attribute Examples
1 – 5 years	Short-term	Delineation
5 – 10 years	Medium-term	Skid resistance/grip
10 – 20 years	Long-term	Road surface rehabilitation
20+ years	Infinite/Negligible	Realignment

(Adapted from iRAP, 2019b)

4.5.2 Operating Speed

Operating speed or mean speed plays a major role in determining the Star Rating Score calculation. In the iRAP methodology, operating speed is the higher speed between the posted speed limit or the 85th percentile speed. **Figure 4.5** shows the iRAP's road attribute risks factor based on the operating speed or mean speed.

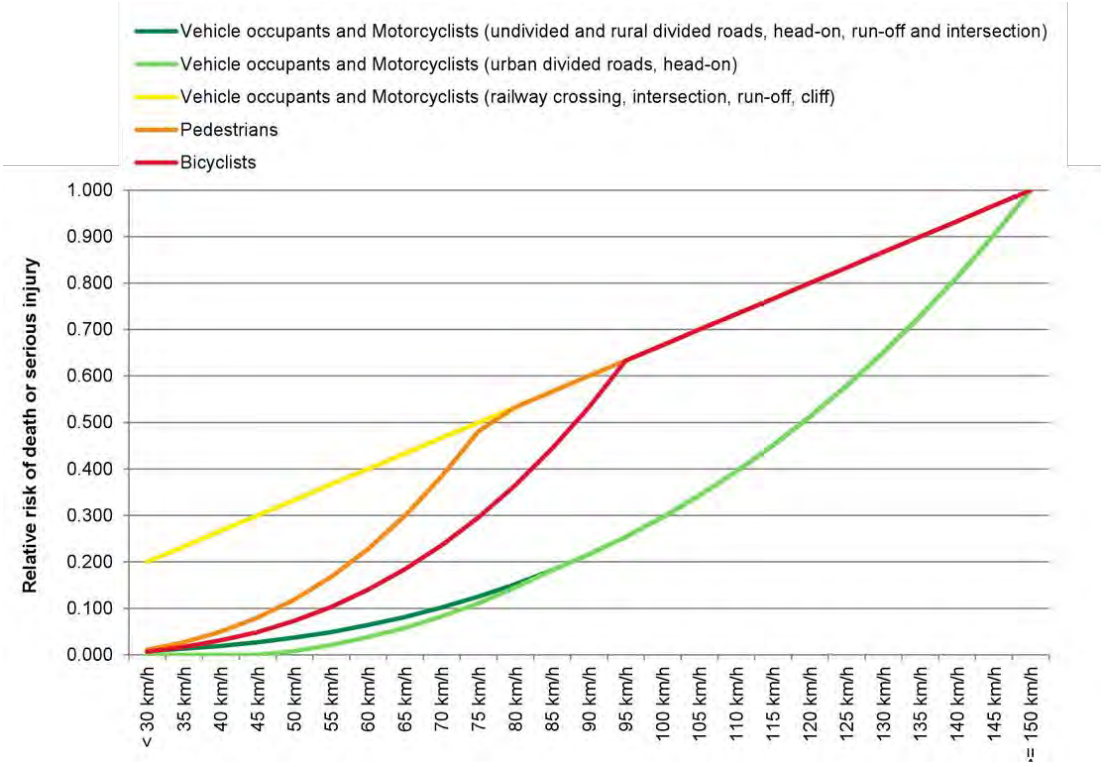


Figure 4.5 Risk factors based on operating speed or mean speed

(Source: From iRAP, 2014c)

There are five sets of risk curves based on the relationship of speed, likelihood or the chance that a crash will be initiated and severity factor according to each road user. In general, the probability of a road accident and injury increases with speed. This is because the braking distance is proportionally increased with the square of the speed thus will influence the chance that a crash will be initiated. Moreover, the human body will be exposed to a higher risk of fatal injury by the fourth power of speed variation which will increase the severity of the crash to a specified road user (Elvik et al., 2004).

According to O'Flaherty (1986), there are two forms of delay that influence the operating speed and mean speed on a section of road. The two forms of delay can be described as follows:

i. fixed delay: delay that is caused by fixed road geometry and road condition such as at an intersection or access point, roundabout, and railway crossing. This delay may occur whether the traffic flow is high or low. In this research, this delay is unlikely to be considered as the road attributes related to intersection and access point will not be considered;

ii. operational delay: delay that is caused by the traffic interaction and reaction of road users towards the changes in the road environment based on their experience. This delay may be caused by internal friction such as an increase in traffic, the stopping vehicle, pedestrian movement, and also irregularities of the road surface.

The effects of delay on operating speed or mean speed of traffic flow caused by traffic volume and road condition may be described by considering the road capacity and speed-flow relationships. The speed-flow relationships may be used to identify the behaviour of traffic flow with regards to road condition. **Figure 4.6** shows the speed-flow model adopted by Odoki and Kerali (2000) from Hoban et al. (1994).

From **Figure 4.6**, when the traffic interactions and internal frictions are negligible, the traffic will travel at a constant speed, S_1-S_3, depending on the type of vehicles, up to the Q_o flow where the traffic interactions will start to affect the speed of interacted vehicles. When the capacity continues to increase, the vehicles that travel at a free-flow constant speed, S_1-S_3, will constantly reduce the speed to the nominal speed capacity, S_{nom}, when the capacity reaching the nominal capacity of the road, Q_{nom}. If the capacity continues to increase further to the ultimate capacity, Q_{ult}, the speed will further reduce to the speed at the ultimate capacity, S_{ult}, which also referred to as jam speed.

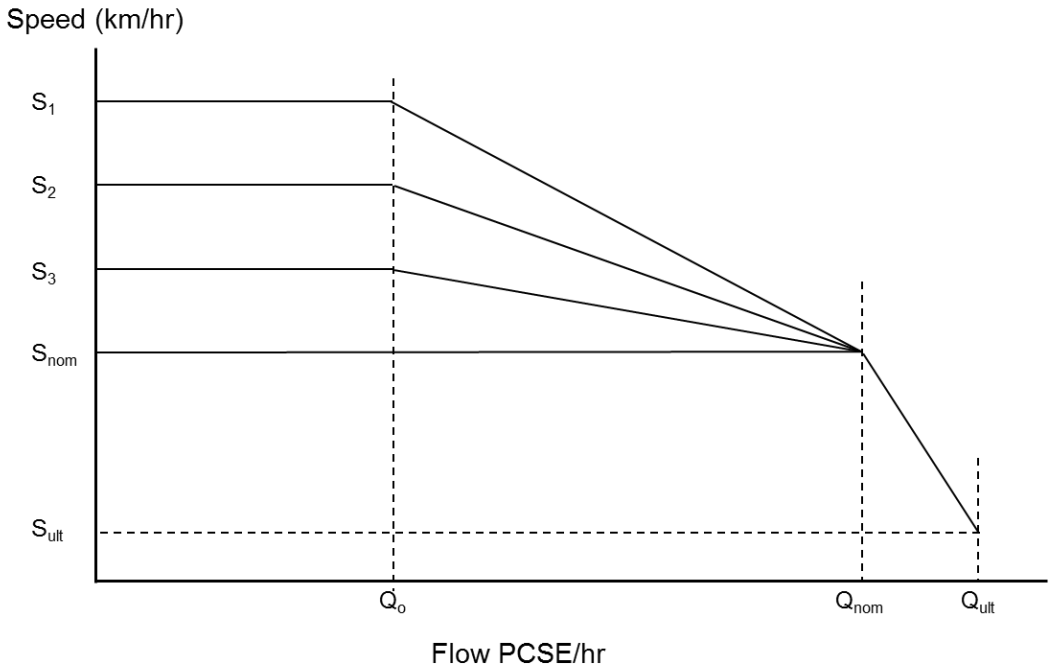


Figure 4.6 Speed-flow model

(Source: Odoki and Kerali, 2000 after Hoban et al., 1994)

In general, the speed will increase with the quality of road condition which may increase the accident risk. Conversely, when the road condition deteriorates, the speed will reduce which will lower the accident risk. For example, from **Figure 4.5**, it is shown that the risk of death or serious injury is considered high for the mean speed above 70km/h. However, this risk is relatively low for the mean speed below 50km/h. Considering this, the definition of operating speed based on iRAP methodology is more accurate in terms of road safety management regardless of road condition and traffic volume.

4.5.3 Framework Limitation

An integrated road asset and road safety management is a total road asset management that systematically and objectively aims to manage road assets concurrently by tackling both road maintenance and road safety issues. It should be able to determine road asset and road safety

performance, respond to the monitored performance with objective implementation policies and may perform the economic evaluation to optimise technical and budget constraints. According to Robinson et al. (1998), a basic approach to any management model, including the integrated one, should follow the basic concept known as the road management cycle as shown in **Figure 4.7**.

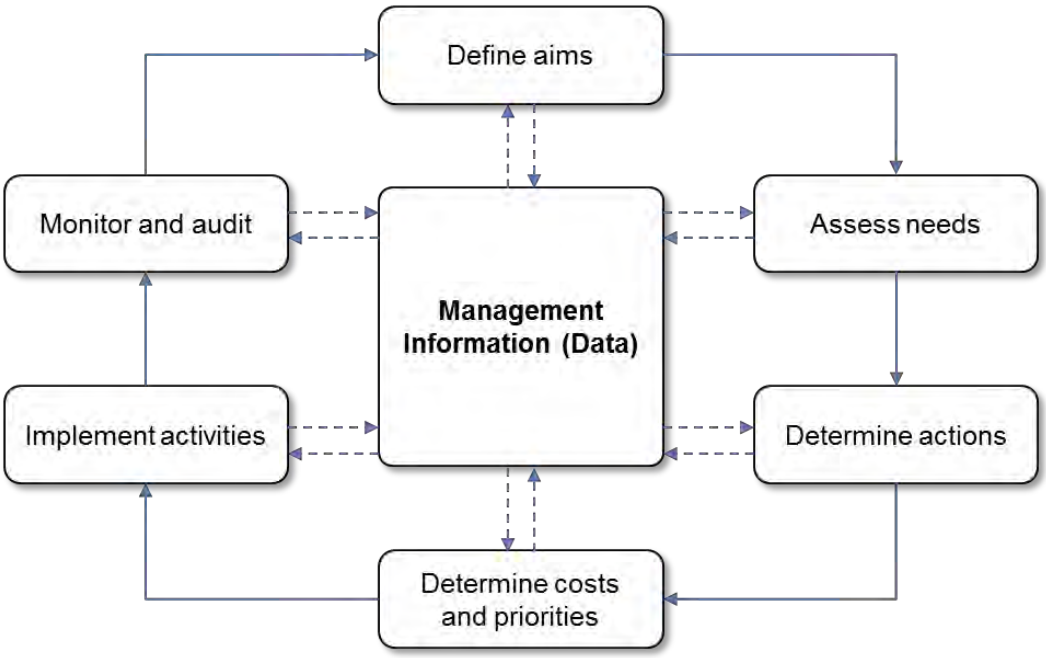


Figure 4.7 The road management cycle

(Source: Robinson et al., 1998)

In this research, several models have been examined. It was felt that the International Road Assessment Programme (iRAP) model for road safety and the Road Network Evaluation Tools (RONET) for road management appraisal are the most suitable for this research. They are chosen for the following reasons:

i. Both tools are readily available online or offline and may be accessed freely by any interested parties for implementation especially from the developing countries;

ii. Both tools are recognised by the international body and highly recommended by the World Bank;

iii. Both tools are a user-friendly model which requires less data and less technical capacity as compared to other more complicated models which will need more time to be explored.

The integration is controlled by the components and structure of both the road safety and road management appraisal models to be integrated. Therefore a generic approach seems to be theoretical whereas a practical integration has to consider specific models. It was felt that any models are appropriate to be integrated in a similar manner as long as it follows the basic concept of the road management cycle.

4.6 Conclusion

This chapter has explained the basic considerations before the development of an integrated model could be established. The basic considerations are related to the road safety assessments and the elements of roads that contribute to road safety performances as well as road asset management. The modelling approach is based on the assessment of road safety performance relative to road deterioration and roadworks.

The International Road Assessment Programme (iRAP) Star Rating Score (SRS) has been proposed to assess road safety performance. The Star Rating Score is based on the crash modification factor which was developed by iRAP. The Road Network Evaluation Tools (RONET) has been chosen for the road assessment tool to evaluate road condition performance and economic analysis.

Five road attributes have been identified as the most significant factors that will be affected by road deterioration. The attributes are delineation, shoulder rumble strip, centreline rumble strips, road condition, and skid resistance/grip. These attributes need to be considered in the life-cycle analysis of road safety performance because their conditions are subjected to deterioration over time.

The following chapter will further investigate the sensitivity of road attributes on the effect of road deterioration and roadworks. Further consideration will be described in **Chapter 5** and **Chapter 6** to develop the road safety degradation model and the countermeasure effects model. It will be the key to developing the analytical framework for this research.

CHAPTER 5

MODELLING ROAD SAFETY DEGRADATION

5.1 Introduction

A systematic road condition assessment is a vital process to carry out maintenance. It involves surveys, data collection activities and analysis prior to the application of the treatment. The quality of the proposed treatment is subject to the accuracy of the condition projection when the treatment is due to be applied (Robinson et al., 1998). Unlike the depth of knowledge on pavement deterioration model, a detailed road safety degradation model is far behind compared to the other. Therefore, the knowledge of predicting road safety performance needs to be developed as part of the road safety appraisal.

This chapter will present the development of the Road Safety Degradation (RSD) model as the first stage of the research questions. This model will form part of the overall analytical framework to integrate road management with road safety. It will play significant contributions in providing the simultaneous assessment of pavement condition and road safety performance with regards to road deterioration.

This chapter will start with an explanation of how the Star Rating is used as an equivalent road standard to represent a basic unit of analysis. This will be followed by the introduction of the approach to predict road safety degradation. This will be followed by a sensitivity analysis to determine the critical road attributes that contribute to road safety performance.

5.2 Star Rating as the Unit of Analysis

There has never been any research that explained the relationship of road safety degradation over time as the road condition deteriorates. In this model, the Risk Factors from the iRAP methodology is used as the variables. It is essential to establish a basic unit of analysis for road safety before any road safety degradation or enhancement parameters can be explored. The basic unit of analysis is a homogeneous road section, which in terms of road attributes and road safety level, that has equivalent design standard and road safety level.

The homogeneity of the road section may be described by a Star Rating band. **Table 5.1** suggests the homogeneous road categories for this research that may be defined using the proposed Equivalent Star Rating Score. As attached in **Appendix 3**, the design standard and road classifications as adapted from REAM (2002) may represent these homogeneous sections. The road attributes assigned for each homogeneous road section are summarised in **Appendix 4**.

Table 5.1 The homogeneous road section as the basic unit of analysis

Star Rating	Equivalent Star Rating Score	Homogeneous Section	[1]Design Standard	[1]Road Class
★★★★★	1.52	High-standard motorway	R6	Expressway
☆☆☆☆	3.70	High-standard rural	R5	Highway
★★★	9.19	Medium-standard rural	R4	Primary Road
★★	16.67	Rural road	R3	Secondary Road
★	31.61	Low-standard rural	R2	Minor Road

[1]Adapted from REAM (2002) based on the equivalent standard to the homogeneous section.

The Equivalent Star Rating Score (ESRS) is derived from the combination of road attributes that represent the respective Star Rating and design standard. The Equivalent Star Rating Scores are assigned based on the class mark of iRAP Star Rating bands as shown in **Table 5.2**. However, as the 1-star band range may be limitless, an appropriate Equivalent Star Rating Score that represents the minimum design standard is assigned.

There are five levels of road safety rating based on the established bands with 1-star considered as the lowest safety level and 5-star as the highest safety level. Each band is set based on road user type (vehicle occupants and motorcyclists, bicyclists and pedestrians) because there are slight differences in the Star Rating Scores equations for each user type. For this research, only vehicle occupants will be considered in the model while the other road user types are not considered. It is important to observe the universal colour coding used for the Star Rating to describe the changes in road safety performance throughout this thesis.

Table 5.2 Star Rating bands based on road user type

Star Rating	Vehicle Occupants and Motorcyclists	Bicyclists	Pedestrians		
			Total	Along	Crossing
★★★★★	0 to < 2.5	0 to < 5	0 to < 5	0 to < 0.2	0 to < 4.8
☆☆☆☆	2.5 to < 5	5 to < 10	5 to < 15	0.2 to < 1	4.8 to < 14
☆☆☆	5 to < 12.5	10 to < 30	15 to < 40	1 to < 7.5	14 to < 32.5
★★	12.5 to < 22.5	30 to < 60	40 to < 90	7.5 to < 15	32.5 to < 75
★	22.5 +	60+	90 +	15 +	75 +

(Source: iRAP, 2013f)

The iRAP administration has developed an online tool to demonstrate and simplify the calculation of the Star Rating Score. The online tool is called the Star Rating Demonstrator and is accessible on their website (https://demonstrator.vida.irap.org/calculate-star). The interactive Star Rating Demonstrator, as well as spreadsheet, will be used in this research as a tool to calculate the Star Rating Score and to demonstrate how the changes in road attributes will affect its road safety performance. This may be achieved by comparing the assessment of the Star Rating Score on two conditions of road attribute. **Figure 5.1** shows the interface of the Star Rating Demonstrator as available on the iRAP's website. The Star Rating Score worked example is attached in **Appendix 5**.

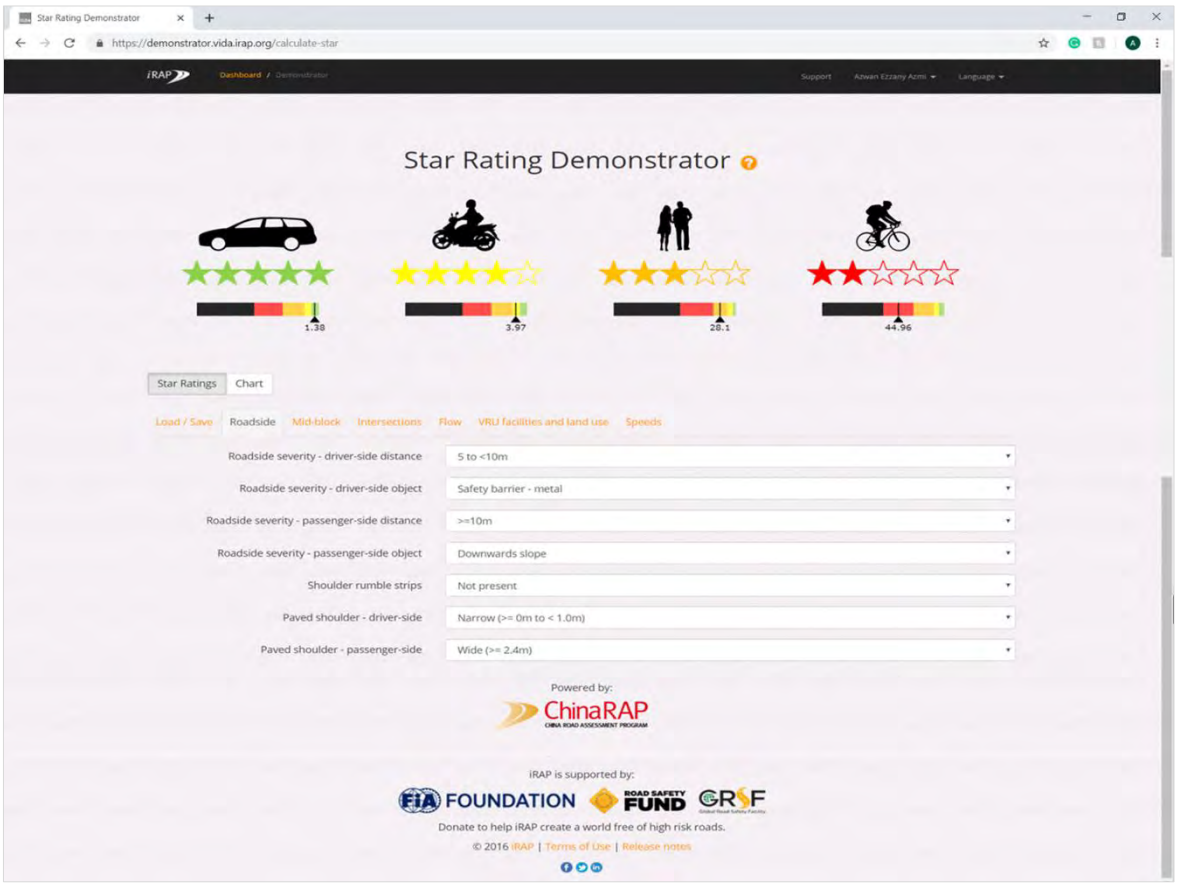


Figure 5.1 The interface of the Star Rating Demonstrator

5.3 Approach to Predict Road Safety Degradation

Prediction is a process to forecast something based on certain condition. In this chapter, a prediction model for road safety degradation is developed based on established pavement prediction models. The prediction model will go through a validation process to determine the accuracy of the road safety degradation value within the tolerance of the model which will be presented in **Chapter 8**.

In contrast to the road safety degradation model, pavement deterioration models are well established. Having known from the brief examination in **Chapter 4** that the factors which will influence road safety degradation are confined within the carriageway, it may be inferred that the deterioration of the road is dominated by the pavement properties. Therefore, it is considered that the pavement deterioration model has a significant influence on the road safety degradation model. Hence, the development of the road safety degradation model should follow a similar approach.

The pavement deterioration model is developed based on condition projection methods which can be grouped into two basic categories (Robinson et al., 1998):

i. Probabilistic
ii. Deterministic

The probabilistic method is a prediction of a range of possible conditions based on a probability function. It is normally used for network analysis to predict the probability of an outcome to road condition over a period of time. This method is not suitable for a project level analysis as it cannot give a detailed work program for a section.

The deterministic method is a prediction of conditions as a precise value of a set outcome for an event. The prediction is based on the mathematical functions of an observed or measured

deterioration. It can be used for network or project analysis as it may provide a detailed work programme for each section. There are three classes of the deterministic method which are normally being used in pavement models namely mechanistic, regression and mechanistic-empirical. The most advanced road appraisal model such as the Highway Development and Management Tool (HDM-4) uses the deterministic mechanistic-empirical model as the method of pavement deterioration prediction.

Furthermore, Morosiuk et al. (2004) have suggested two types of models that can be used for predictive purposes namely as follows:

i. The *absolute model* that gives the condition at a particular point in time as a function of the independent variables. The disadvantage of the absolute model is that it is usually confined to a specific condition it is based on. This limits the model to be readily applied in different condition;
ii. The *incremental model* that predicts the change in condition from an initial state as a function of the independent variables. The incremental model can be applied to a variety of different initial conditions and offer more flexibility.

Pavement strength and road roughness are the most important factors considered in a common pavement performance model. Pavement strength is referred to as an empirical relationship between thickness and strength of pavement layers that are combined using the sum of their product (Morosiuk et al., 2004). For road safety, this will not contribute to a significant extent to road safety performance as it is confined to the layers under the pavement surface and has no direct interaction with vehicles or drivers. Therefore, it is not necessary to consider pavement strength in the road safety degradation model.

Moreover, road roughness represents the unevenness of a road surface. Therefore, it may directly associate with road safety degradation as it directly interacts with the vehicle and

drivers and may become a primary cause of wear and tear on vehicles. Roughness may represent various kinds of distresses such as cracks, potholes, and rutting as shown in **Figure 5.2**.

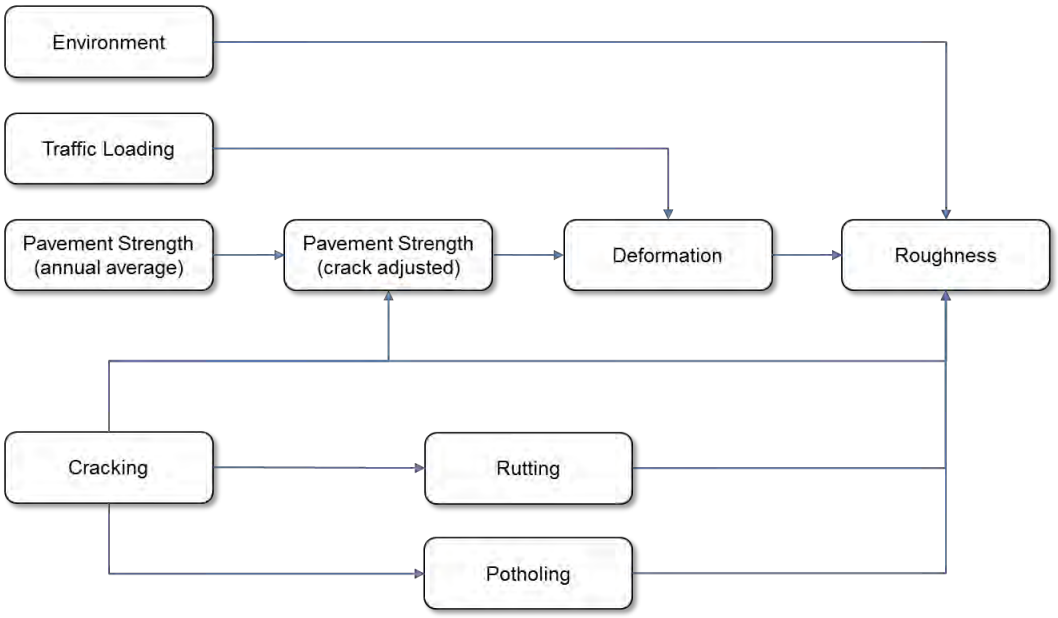


Figure 5.2 Dependence of road roughness to various distresses

(Source: Adapted from Morosiuk et al., 2004)

In an advanced road management appraisal model such as the HDM-4, pavement deterioration is modelled in terms of several road defects such as roughness, cracking, rutting, ravelling and potholes (Odoki and Kerali, 2000). These distresses may be modelled separately in a pavement management system to provide the ideal maintenance treatment for a particular section of the road. However, in the iRAP Road Attribute Risk Factors, road roughness may be associated with a specific attribute namely Road Condition (iRAP, 2013d).

It is a challenge to consider a group of road defects as a collective input for a general Road Condition attribute as available in iRAP methodology. Furthermore, the development of a road

safety degradation model based on structural empirical data is not within the scope of this research. Therefore, a probabilistic method with consideration on Skid Resistance/Grip and Road Condition will be used for this research to develop a simplified model for road safety degradation that briefly assimilates the pavement deterioration model. The proposed model will be used to predict the change in road safety performance over the analysis period.

5.4 Sensitivity Analysis

As identified before in **Chapter 4**, the road attributes that respond to road deterioration in Star Rating Score are Delineation, Shoulder Rumble Strip, Centreline Rumble Strip, Road Condition, and Skid Resistance/Grip. **Table 5.3** shows the road attributes and their respective category that may contribute to road safety degradation.

Table 5.3 Road attributes that contribute to road safety degradation

Road Attribute	Conditions	Risk Factors
Shoulder rumble strips	• Not present • Present	• 1.25 • 1.00
Centreline rumble strips	• Not present • Present	• 1.20 • 1.00
Delineation	• Poor • Adequate	• 1.20 • 1.00
Road condition	• Poor • Medium • Good	• 1.40 • 1.20 • 1.00
Skid resistance / grip	• Poor (Sealed/Unsealed) • Medium (Sealed) • Adequate (Sealed/Unsealed)	• 2.00 / 5.50 • 1.40 • 1.00 / 3.00

(Adapted from iRAP, 2019b)

Considering the number of conditions involved, the total number of possible outcomes is 2 x 2 x 2 x 3 x 3 or equivalent to 72 outcomes. Therefore, a brief sensitivity analysis has to be carried out to determine the most sensitive road attribute effects on road safety degradation that may reduce the number of possible outcomes. **Table 5.4** to **Table 5.8** shows the result of the sensitivity analysis represented as the different value of the Star Rating Score between the two most extreme condition in each attribute.

Table 5.4 Difference value of the Star Rating Score (Delineation)

Star Rating	Delineation		Difference	Percentage Difference (%)
	Adequate	Poor		
★★★★★	1.38	1.66	0.28	20.29
☆☆☆☆	4.59	5.41	0.82	17.86
★★★	6.76	8.11	1.35	19.97
★★	14.83	17.72	2.89	19.49
★	24.39	29.27	4.88	20.00

Table 5.5 Difference value of the Star Rating Score (Centreline Rumble Strip)

Star Rating	Centreline Rumble Strip		Difference	Percentage Difference (%)
	Present	Not Present		
★★★★★	1.38	1.38	0.00	0.00
☆☆☆☆	4.08	4.59	0.51	12.50
★★★	7.48	8.11	0.63	8.42
★★	17.18	17.72	0.54	3.14
★	27.64	29.27	1.63	5.90

Table 5.6 Difference value of the Star Rating Score (Shoulder Rumble Strip)

Star Rating	Shoulder Rumble Strip		Difference	Percentage Difference (%)
	Present	Not Present		
★★★★★	1.10	1.38	0.28	25.45
☆☆☆☆	4.38	4.59	0.21	4.79
★★★	7.25	8.11	0.86	11.86
★★	14.91	17.72	2.81	18.84
★	25.37	29.27	3.90	15.37

Table 5.7 Difference value of the Star Rating Score (Road Condition)

Star Rating	Road Condition		Difference	Percentage Difference (%)
	Good	Poor		
★★★★★	1.38	1.93	0.55	39.86
☆☆☆☆	3.87	5.22	1.35	34.88
★★★	8.11	11.36	3.25	40.07
★★	17.72	24.67	6.95	39.22
★	29.27	40.97	11.70	39.97

Table 5.8 Difference value of the Star Rating Score (Skid Resistance/Grip)

Star Rating	Skid Resistance/Grip		Difference	Percentage Difference (%)
	Adequate	Poor		
★★★★★	0.95	2.76	1.81	190.52
☆☆☆☆	3.87	7.74	3.87	100.00
★★★	8.11	16.23	8.12	100.12
★★	17.72	35.45	17.73	100.06
★	29.27	58.53	29.26	99.97

From **Table 5.4** to **Table 5.8**, the sensitivity analysis that has been carried out has demonstrated that there is a clear pattern of differences in the calculated Star Rating Scores. The results can be divided into two groups, namely, pavement markers which are associated with Centreline Rumble Strip, Shoulder Rumble Strip and Delineation, and secondly, pavement condition which is related to Road Condition and Skid Resistance / Grip.

The Star Rating Scores for Centreline Rumble Strip, Shoulder Rumble Strip and Delineation have recorded maximum differences of 4.88, 1.63 and 3.90 points respectively. The differences are not significant against a lower band with an average percentage difference of less than 20%. The differences caused by the pavement markers are much lower when compared to the differences due to the pavement condition attributes. The Road Condition and Skid Resistance/Grip have recorded the differences of 11.70 and 29.26 points with an average percentage difference of 38.80% and 118.13% respectively. This is a significant piece of evidence that shows the sensitivity of pavement condition on the road safety level. The pavement condition also has triggered road safety degradation to reduce the safety level on certain combinations.

Therefore, based on the Star Rating Score, the attributes related to pavement marking may be ignored as they do not significantly contribute to road safety degradation. Thus, only the Skid Resistance/Grip and Road Condition will be considered in the road safety degradation model. To simplify the road safety degradation model, the Star Rating Score will be used as a single index of degradation function that combines the effects of Skid Resistance/Grip and Road Condition.

5.5 Proposed Road Safety Degradation Index

Similarly, the combined effect of Skid Resistance/Grip and Road Condition on road safety degradation could be assessed. There are nine possible combinations or outcomes which lead to a wide range of road safety degradation caused by both Skid Resistance/Grip and Road Condition. **Table 5.9** shows the effects of Skid Resistance/Grip and Road Condition combinations on road safety degradation. It is important to observe the changes of colour coding that indicates the reduction of road safety level for each Star Rating caused by the combination of Skid Resistance/Grip and Road Condition.

Table 5.9 The effects of Skid Resistance/Grip and Road Condition to Road Safety

Skid Resistance	Adequate			Medium			Poor		
Road Condition	Good	Medium	Poor	Good	Medium	Poor	Good	Medium	Poor
★★★★★	1.38	1.66	1.93	1.93	2.32	2.70	2.76	3.31	3.86
☆☆☆☆	3.87	4.55	5.22	5.42	6.36	7.31	7.74	9.09	10.44
☆☆☆	8.11	9.73	11.36	11.36	13.65	15.90	16.23	19.47	22.71
★★	17.72	21.20	24.67	24.81	29.67	34.54	35.45	42.39	49.34
★	29.27	35.12	40.97	40.97	49.17	57.36	58.53	70.24	81.94

From the result of the analysis as summarised in **Table 5.9**, a pattern of road safety degradation may be identified and clearly marks the road safety level reduction due to the combined effects of Skid Resistance/Grip and Road Condition. For example, a 5-star road will remain as 5-star until the Skid Resistance/Grip becomes medium and Road Condition becomes poor which will

reduce the road safety level to 4-star. The effects of road safety level reduction for each deterioration combination is shown by the arrows pattern in **Table 5.10**.

Table 5.10 The pattern of road safety degradation and the proposed Road Safety Degradation Index

Star Rating	Road Safety Degradation (RSD)								
★★★★★									
★★★★									
★★★									
★★									
★									
RSD Index	E1	E1	E2	E2	E3	E4	E4	E4	E5
Skid Resistance[1]	A	A	A	B	B	B	C	C	C
Road Condition[2]	A	B	C	A	B	C	A	B	C

[1]*A: Adequate B: Medium C: Poor*
[2]*A: Good B: Medium C: Poor*

From the arrows pattern, all the nine deterioration combinations may be divided into five categories of Road Safety Degradation Index (RSDI) namely E1, E2, E3, E4, and E5. **Table 5.10** also shows the proposed Road Safety Degradation Index suggested based on the unique arrows pattern formed by the deterioration combination effects. The indexes which may indicate the severity level that can be contributed by the deterioration combinations are classified based on the reduction of road safety level and characterised as follows:

i. Very Good (E1): can be considered as the minimum combined effect on road safety as they do not cause any road safety degradation;

ii. Good (E2): will reduce the road safety level from 4-star to 3-star and from 2-star to 1-star;

iii. Fair (E3): will reduce the road safety level from 4-star to 3-star, from 3-star to 2-star and from 2-star to 1-star;

iv. Poor (E4): will reduce the road safety level from 5-star to 4-star, from 4-star to 3-star, from 3-star to 2-star and from 2-star to 1-star;

v. Very Poor (E5): will reduce the road safety level from 5-star to 4-star, from 4-star to 3-star, from 3-star to 1-star and from 2-star to 1-star.

5.6 Proposed Road Safety Degradation Model

The characteristics of the abovementioned Road Safety Degradation Index pattern is in line with the sigmoidal curve of initiation and progression phases of distress as adopted in the HDM-4 (Morosiuk et al., 2004) and the cracking progression model as adopted in the RONET which has been explained in **Chapter 4** (Archondo-Callao, 2009). The sigmoidal curve established for the road deterioration model used in most road management appraisal may be overlayed on the road safety degradation to indicate the relationship between both deterioration models. **Figure 5.3** shows the relationship of how the pavement deteriorates with time and how the Road Safety Degradation Index change as the vector of road safety degradation relative to the pavement deterioration. From this graph, it can be concluded that the road safety level may turn to Poor when the road condition has reduced just 20% of its capacity.

To model how the Road Safety Degradation Index change with time, it is necessary to establish a Markov probability transition matrix as a universal model as shown in **Table 5.11** and **Table 5.12** (Robinson et al., 1998). **Table 5.11** shows the road safety degradation change vector that

indicates the sequence number for road safety condition changes relative to a different deterioration combination. Then, a transition matrix based on the previous sequence can be set up as shown in **Table 5.12**. This transition matrix may define the probability that a safety level in an initial state would deteriorate to a particular future safety level.

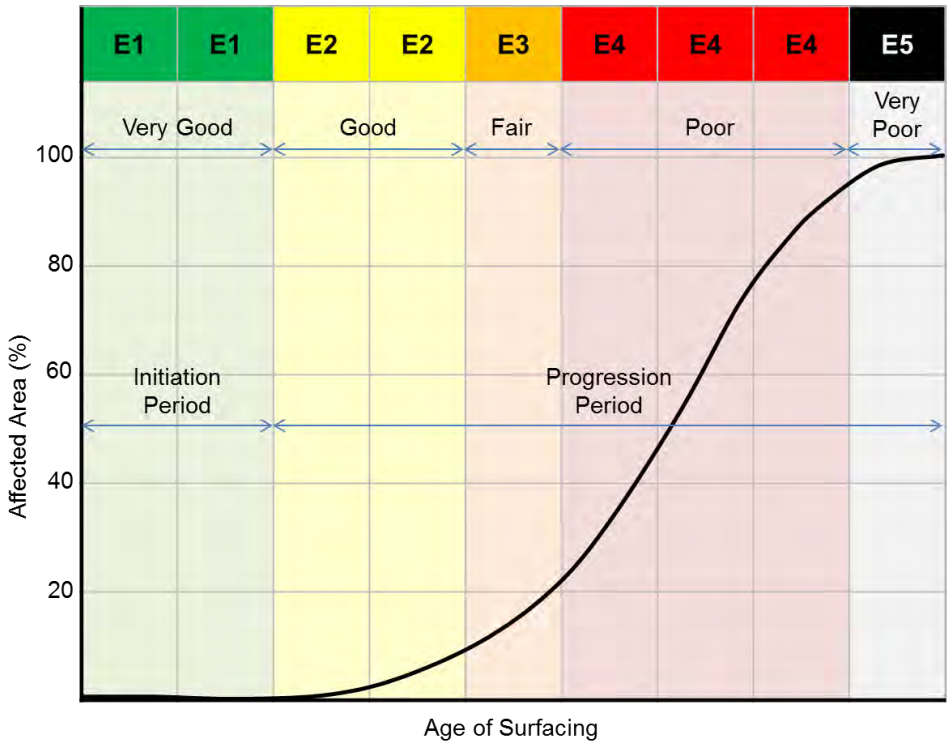


Figure 5.3 Initiation and progression phases of road safety degradation

Table 5.11 Condition state of road safety degradation change vector

Road Condition	Skid Resistance		
	Adequate	Medium	Poor
Good	1	2	3
Medium	4	5	6
Poor	7	8	9

Table 5.12 Transition matrix of road safety degradation

Initial Condition State	Probability of Future Safety Rating								
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
1	p(1)	q(1)	0	0	0	0	0	0	0
2	0	p(2)	q(2)	0	0	0	0	0	0
3	0	0	p(3)	q(3)	0	0	0	0	0
4	0	0	0	p(4)	q(4)	0	0	0	0
5	0	0	0	0	p(5)	q(5)	0	0	0
6	0	0	0	0	0	p(6)	q(6)	0	0
7	0	0	0	0	0	0	p(7)	q(7)	0
8	0	0	0	0	0	0	0	p(8)	q(8)
9	0	0	0	0	0	0	0	0	1

Note: p(j) is the probability of a pavement staying in safety rating j during one duty cycle, and q(j) = 1 - p(j) is the probability of a pavement's transiting down to the next safety rating (j + 1) during one duty cycle.

This model can be used to predict future road safety degradation relative to road deterioration at any particular time of the analysis period (Butt et al., 2004). Butt et al. (2004) have successfully demonstrated an identical methodology to determine the pavement deterioration process based on a probabilistic approach. This approach will be replicated to simulate the life-cycle road safety performance analysis for this research. The validation process of the proposed Road Safety Degradation Model will be presented in **Chapter 8**.

5.7 Conclusion

This chapter has presented the development of the road safety degradation model. The road safety degradation model is one of the important aspects of this research as it may help to answer the first stage of this research questions. From the development of the road safety

degradation model, the approach to determine the relationship between road deterioration and road safety level may be established.

In this approach, The iRAP's Star Rating Score has been used as the basis to calculate the road safety level between two conditions. From five road attributes that may contribute to road safety degradation, only two attributes were determined to be sensitive in predicting road safety degradation that is Skid Resistance/Grip and Road Condition. Between these two road attributes, the Skid Resistance/Grip has been identified as more influential in reducing road safety level. This finding has suggested the sequence on how the state of road safety level will change towards the deterioration combinations.

From the sensitivity analysis also, a pattern of deterioration characteristics has been discovered. This pattern has suggested a severity level that can be contributed by the deterioration combinations. From the discovered degradation sequence and the deterioration severity level, it has been identified that the degradation may follow the sigmoidal curve established in many road deterioration models. It is suggested that the Markov probability method is used to predict the future road safety degradation model. This has formed part of the integral approach in establishing the relationship between road deterioration and road safety degradation.

In the next chapter, a range of treatment option will be explored to ultimately develop a countermeasure effects model. The countermeasure effects model will be developed to define the effects of each treatment with regards to road safety performance. It will be used in this research analytical framework to evaluate the effects of treatment on the road safety level.

CHAPTER 6

MODELLING COUNTERMEASURE EFFECTS

6.1 Introduction

This chapter will present the final part of the model development for the Countermeasure Effects (CE) model. This model will form part of the overall analytical framework to integrate road management and road safety. Stage 2 and Stage 3 of the research questions will be presented in this chapter. It offers significant contributions to road management by providing simultaneous assessment of pavement condition and road safety performance with the view to define appropriate pavement treatments and road safety countermeasures.

This chapter will first explain the important terminology related to road asset management activities that focuses on physical works. The use of terms such as roadwork, treatment and countermeasure will be established in the context of this research. This is important to differentiate their focus in terms of road condition or road safety.

This will be followed by the introduction of the approach to predict countermeasure effects in terms of road safety performance. A list of possible treatment options available to tackle both road maintenance and road safety are presented. These treatment options will be examined in terms of road maintenance and road safety improvement. Intervention criteria are identified based on the treatment priorities and their possible roadwork effects. A sensitivity analysis is carried out on the possible roadwork effects to determine the countermeasure effects. Ultimately, the proposed Countermeasure Effects model will be presented.

6.2 Definition

Morosiuk et al. (2004) have defined the term *roadwork* as "any change to the physical characteristics of a road and may embrace operations ranging from simple maintenance, such as cleaning detritus from the road surface to the construction of a new road link". Robinson et al. (1998) have defined the term *activity* as "the works to undertake road maintenance, new construction, improvement and the like".

In the wide context of this research, those terms will be defined by their specific effects on road infrastructure in terms of road asset preservation or road safety enhancement. The terms *roadwork* and *activity* will be referred to as any types of works that change the physical characteristics of a road to elevate the purpose and performance of road infrastructure.

The works may include construction work or maintenance work. The terms of *treatment* and *countermeasure* will be referred to as specific works that tackle specific issues. *Treatment* may cover the work that tackles road maintenance and road safety issues and *countermeasure* will specifically be referred to the work that elevates road safety.

6.3 Approach to Predict Countermeasure Effects

It is important to identify all possible roadwork activities ranging from the construction of a new road to the most basic maintenance works. This may be achieved by investigating all the treatment options offered by both road asset management and road safety appraisal models. To investigate the road safety effects of each treatment, it is necessary to compare the road safety level of two scenarios namely pre-construction and post-construction, which indicate the road safety performance before and after a range of treatments is applied. This scenario may be derived from **Eq. 3.2** when the rate of deterioration, *dRSR*, is assumed to be stopped, as explained by the following equations:

$$RSR_{n+1} = RSR_n + dRSR + dRSR_{CE} \quad \textbf{(6.1)}$$

when $dRSR = 0$,

$$RSR_{n+1} = RSR_n + dRSR_{CE} \quad \textbf{(6.2)}$$

hence,

$$dRSR_{CE} = RSR_{n+1} - RSR_n \quad \textbf{(6.3)}$$

where,

RSR_n = Pre-construction road safety rating;

RSR_{n+1} = Post-construction road safety rating;

$dRSR$ = Road safety rating decrement due to deterioration

$dRSR_{CE}$ = Road safety rating increment due to countermeasure effects.

For each homogeneous road section in terms of Star Ratings, there are five levels of pre-construction Star Ratings that should be considered. Each possible treatment option will be assigned to each of the homogeneous road sections and evaluate in terms of road safety performance. Changes to road attributes will be investigated for each of the possible roadwork activities. The evaluation will be calculated based on the Star Rating Score (SRS) to identify the post-construction Star Ratings.

In general, each treatment may increase the existing road safety level to a better rating or may just preserve the existing level. Therefore, the possible Countermeasure Effects may be determined based on the possible transition of the Star Rating that may occur. The magnitude of the transition may be predicted as a possible category of Countermeasure Effects. A sensitivity analysis of each treatment will be carried out to evaluate the magnitude of the rating changes to categorise each treatment into the appropriate Countermeasure Effects Index (CEI).

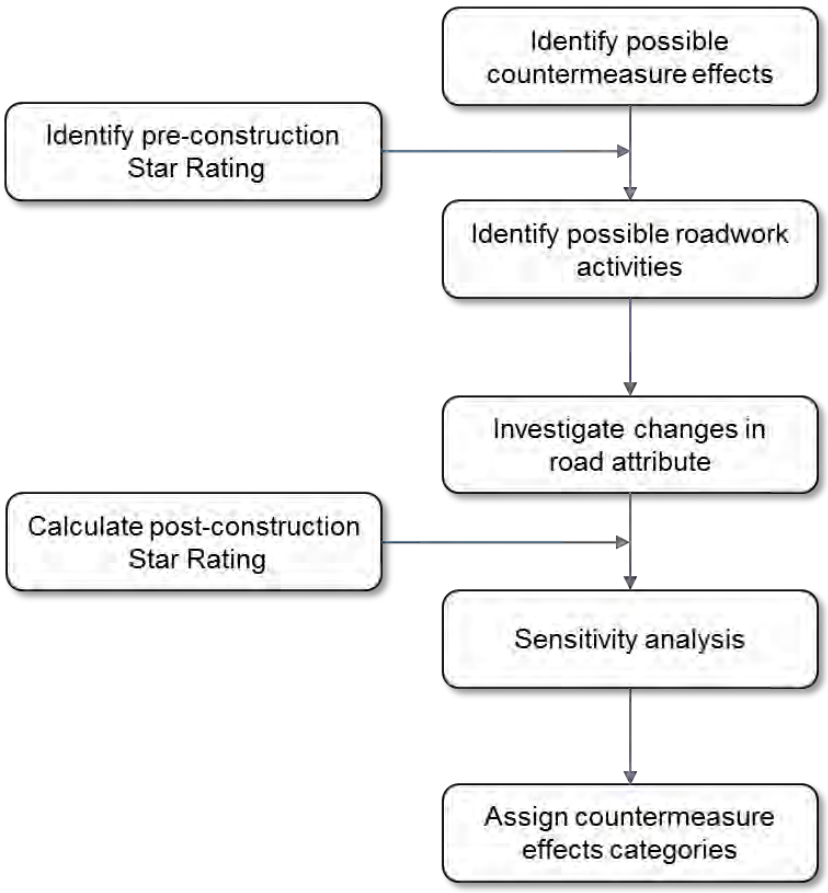


Figure 6.1 Approach to predict countermeasure effects

The Countermeasure Effects index will later be used to evaluate the long-term road safety performance based on the main analytical framework of this research. The effects of countermeasure in terms of road condition indicator will not be evaluated in this exercise as they may be evaluated as Work Effects in road asset management tools in **Chapter 10**. **Figure 6.1** shows the approach used to predict the Countermeasure Effects of treatment on road safety rating.

6.4 Proposed Countermeasure Effects Index

To predict the countermeasure effects, it may be necessary to identify whether any road safety condition can be restored or increased. **Figure 6.2** shows the possible countermeasure effects

based on pre and post-construction of road safety Star Rating. It is necessary to note the use of different colours to show different countermeasure effect for each level of change. For instance, black indicates no change as the lowest countermeasure effect, red indicates one level, orange indicates two levels, yellow indicates four levels and green indicates five levels as the highest countermeasure effect.

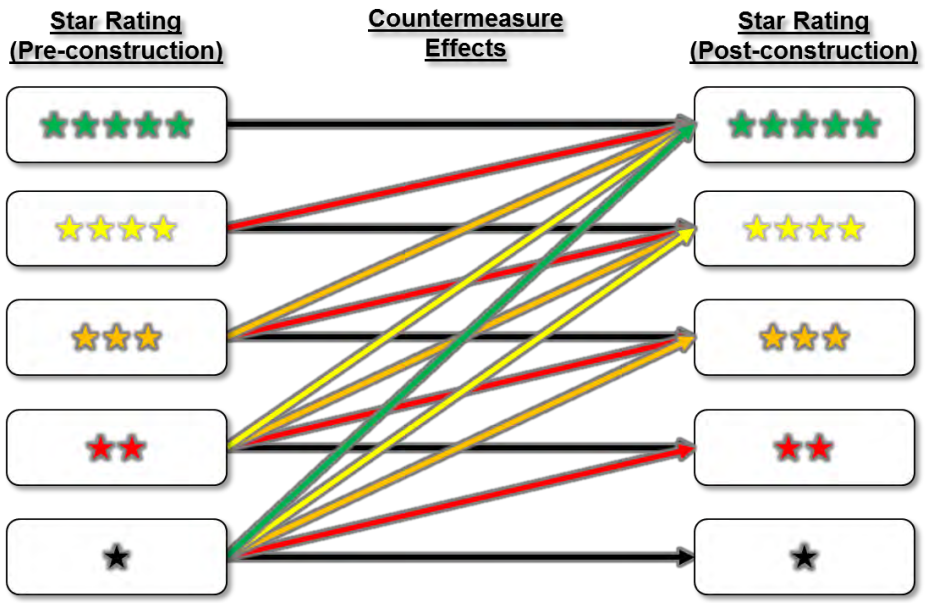


Figure 6.2 Possible countermeasure effects

The countermeasure effects vary in terms of the magnitude of the change that they bring to the road safety level. From the colour indicator, in general, there are five levels of magnitude which will possibly be affected by each countermeasure towards road safety level. Each countermeasure may either retain the same road safety level or increase the road safety level between one to four levels. Based on **Figure 6.2**, it may be suggested that there are 15 combinations of possible countermeasure effects as summarised in **Table 6.1** which can be categorised by the Countermeasure Effects Index (CEI) or roadworks standard as follows:

i. Very High Standard (C1) can be considered as the highest standard of countermeasure that may bring the road safety level up to four levels from 1-star to 5-star;

ii. High Standard (C2) will increase the road safety level up to three levels from 1-star to 4-star and from 2-star to 5-star;

iii. Medium Standard (C3) will increase the road safety level up to two levels from 1-star to 3-star, from 2-star to 4-star and from 3-star to 5-star;

iv. Low Standard (C4) will increase the road safety level up to one level from 1-star to 2-star, from 2-star to 3-star, from 3-star to 4-star and from 4-star to 5-star;

v. Very Low Standard (C5) can be considered as the lowest standard of countermeasure that may keep the road safety level on the same level also known as the "Do Minimum" standard.

Table 6.1 Summary of possible countermeasure effects

Star Rating	Countermeasure Effects														
★★★★★															
★★★★															
★★★															
★★															
★															
CE Index	C1	C2	C2	C3	C3	C3	C4	C4	C4	C4	C5	C5	C5	C5	C5

6.5 Possible Roadwork Activities

The selection of activities or treatments to meet specific roadwork objectives should follow a certain procedure to ensure maximum benefits can be gathered from each road fund expenditure. Based on Robinson et al. (1998), there are two basic procedures as follows:

i. Scheduled: work to be carried out is fixed at a certain amount or at specific time intervals throughout a specific period;
ii. Condition-responsive: work to be carried out when the asset condition reaches a certain fixed point or intervention level.

In general, the roadwork activities or treatments may be categorised based on the time of implementation and the budgeting mechanism. The roadwork categories can be described as routine work, periodic work, special work, upgrading work and development work as follows (Robinson et al., 1998):

i. *Routine work* is the scheduled work that may need to be carried out on cyclic-based and in a certain period of the year. It is normally funded from a recurrent budget which is budgeted yearly. The activities are patching potholes, crack sealing, grass cutting, cleaning road furniture and cleaning drains.
ii. *Periodic work* is a planned work that may need to be carried out as condition-based to restore or improve the condition of the asset. It is typically funded from a recurrent budget or capital budget which is specially budgeted for a special purpose. The activities are resurfacing work and overlay work.
iii. *Special work* is unplanned work that has to be carried out as a result of an unforeseen event or to prevent the unwanted situation to occur. It is typically

funded from special or contingency funds and sometimes from the recurrent budget. The activities are emergency work, winter work and post-disaster work.

iv. *Upgrading work* is a planned work that may need to be carried out to elevate the purpose and performance of the road by adding additional features. It is typically funded from a recurrent budget or capital budget which is specially budgeted for a special purpose. The activities are installing road furniture and installing street lighting.

v. *Development work* is a planned work that may be carried at discrete points in time. It is typically funded from a capital budget. The activities are widening of road, realignment and construction of new section.

The range of the roadwork activities is so wide; ranging from as simple as a rubbish collection to the construction of a new highway. For this research, to ensure that the treatment options cover all class of roadworks, it is necessary at least to consider all treatments offered in both road management and road safety appraisal.

6.5.1 Road Management Activities

Since this work uses Road Network Evaluation Tools (RONET) as the appraisal tool, it is necessary to note that the roadwork activities considered in the tool are classified in the following manner (Archondo-Callao, 2009):

i. *Recurrent Maintenance Works*: annual routine maintenance works on and outside of the carriageway;

ii. *Capital Road Works*:

   a. *New Construction*: Construction of new road including the upgrading of the existing road;

b. *Periodic Maintenance*: Pavement treatment applied to roads in a good and fair condition such as resurfacing and surface treatment;

c. *Rehabilitation*: Pavement treatment applied to roads in poor and bad condition such as strengthening and reconstruction of the existing pavement structure.

The possible capital roadwork classes are summarised in **Table 6.2**.

Table 6.2 Possible capital road works available in RONET

Road Condition	Roadwork Type	Roadwork Class
Good	Preventive Treatment	Periodic Maintenance
Fair	Resurfacing	Periodic Maintenance
Poor	Strengthening	Rehabilitation
Very Poor	Reconstruction	Rehabilitation
No Road	New Construction	New Construction

(Source: Adapted from Archondo-Callao, 2009)

In general, the treatment options available in the RONET are confined to limited options which may tackle the pavement and road condition issues including the option of constructing a new road. The treatments cover the recurrent aspect of routine maintenance which may include patching pothole, crack sealing, shoulder degradation, grass cutting, road furniture cleaning, and culvert and drainage cleaning. For the periodic maintenance, activities such as road resurfacing, pavement structure strengthening and reconstruction are the major roadworks to solve the pavement deterioration.

The appraisal tools also may provide the construction of a new road. This includes the upgrading of the existing road which may add a new alignment to the overall road network.

Even though road management activities are mainly related to pavement performance, they can indirectly contribute to road safety.

6.5.2 Road Safety Activities

The road safety countermeasures offered in the International Road Assessment Programme (iRAP) which is used in this research consist of 42 types of treatment as available in the iRAP's Road Safety Toolkit (iRAP, 2019). The list of treatments that are referred to in the toolkit as Safer Road Treatment (SRT) is provided in **Table 6.3**. Details of the cost, treatment life and the effectiveness of each treatment in terms of percentage reduction of accident risks are summarised in **Appendix 6**.

The treatment options as offered by iRAP's Road Safety Toolkit consist of various class of roadwork exclusively for the purpose that they are designed to tackle various road safety issues. Most of the countermeasures may be considered as upgrading work if the existing road might experience a significant change and added value to the functionality. Undoubtedly, some of the countermeasures may be considered as periodic work in which they may indirectly contribute to restoring the road condition on the existing road such as the Road Surface Rehabilitation and Skid Resistance. Some countermeasures may create new assets such as Duplication and Horizontal Realignment which may be considered as development work.

In **Table 6.3**, the list of treatments is hierarchically classified based on implementation and budgetary criteria as an indication of how they are practically carried out by most road agencies. Some countermeasures that target the other occupants such as pedestrian, bicyclist and motorcyclist are extracted from the classes and may not be considered in this research as this research will focus only on the vehicle occupants.

Table 6.3 The Safer Road Treatment extracted from iRAP's Road Safety Toolkit

Safer Road Treatment	
Development	**Periodic**
1. Duplication	23. Central Hatching
2. Intersection - Grade Separation	24. Road Surface Rehabilitation
3. Realignment - Horizontal	25. Skid Resistance
4. Realignment - Vertical	26. Rumble Strips
5. Service Road	27. Speed Management
	28. Street Lighting
Upgrading	29. Traffic Calming
6. Additional Lane	
7. Central Turning Lane Full Length	**Routine**
8. Intersection - Delineation	30. Delineation
9. Intersection - Roundabout	31. Roadside Safety - Hazard Removal
10. Intersection - Signalise	32. Shoulder Sealing
11. Intersection - Turn Lanes (Signalised)	33. Sight Distance (obstruction removal)
12. Intersection - Turn Lanes (Unsignalised)	
13. Lane Widening	**Other Occupants (Not Applicable)**
14. Median Barrier	34. Bicycle Facilities
15. One Way Network	35. Median Crossing Upgrade
16. Parking Improvements	36. Motorcycle Lanes
17. Railway Crossing	37. Pedestrian Crossing - Grade Separation
18. Regulate Roadside Commercial Activity	38. Pedestrian Crossing - Signalised
19. Restrict/Combine Direct Access Points	39. Pedestrian Crossing – Unsignalised
20. Roadside Safety - Barriers	40. Pedestrian Fencing
21. School Zones	41. Pedestrian Footpath
22. Sideslope Improvement	42. Pedestrian Refuge Island

(Source: iRAP, 2019)

6.6 Intervention Criteria

The implementation of road management and road safety projects are based on certain intervention criteria. Morosiuk et al. (2004) addressed that the intervention criteria for implementing a new road project or road maintenance work may subject to time, traffic,

geometry, pavement structure, pavement condition, work history, environment condition, adjacent lane and road features, road function and land use, and earthwork and drainage.

For road safety countermeasure, Baguley (1995) indicated that three variables are set as the intervention criteria as shown below:

i. Number and severity of the accident: e.g. fatality, serious injury, slight injury and damage only (in terms of numbers and severity weighting factors);
ii. Unit of coverage area: e.g. radius, length and area considered;
iii. Intervention period: e.g. 3-years, 12-month or seasonal.

Considering the intervention criteria as suggested by Baguley (1995), the assessment may require excessive data on road accident statistic throughout the network. This will also ignore the purpose of the International Road Assessment Programme (iRAP) in evaluating road safety performance and tackling road safety issues worldwide. Therefore, it is suggested that the iRAP's Star Rating is used as the intervention criteria for road safety project implementation as below:

i. 5-star: Very good road safety level which may require minimum countermeasures to sustain;
ii. 4-star: Good road safety level which may require low standard countermeasures to sustain or to increase the road safety level;
iii. 3-star: Medium road safety level which may require low to medium standard countermeasures to sustain or to increase the road safety level;
iv. 2-star: poor road safety level which may require medium to high standard countermeasures to increase the road safety level;
v. 1-star: Very poor road safety level which may require high to very high standard countermeasures to increase the road safety level.

6.6.1 Priorities

The roadwork activities or treatment will be triggered if one or a combination of the intervention criteria are met. If there is more than one treatment triggered, the treatment with the highest ranking will be given the priority to be implemented. **Table 6.4** shows the ranking of road management activities that will be used in this research.

Table 6.4 Ranking of the road management activities

Work Type	Work Activity	Cost Range	Ranking
New construction	New construction	High	1
Reconstruction	Full reconstruction	Medium to High	2
Rehabilitation	Strengthening	Medium	3
Resurfacing	Overlay	Low to Medium	4
Preventive treatment	Surface treatment	Low	5
Routine maintenance	Pothole patching	Low	6

As suggested by Morosiuk et al. (2004), a treatment ranking may be set based on the scope of the work. For example, a more comprehensive treatment will be given a higher priority. In general, the scope of work that cost more and more effective may get a higher priority. This may suggest that the norm may be used in evaluating the ranking of the road safety countermeasure based on cost and the effectiveness of the treatment.

6.6.2 Possible Roadwork Effects

Morosiuk et al. (2004) have suggested immediate roadwork effects based on the characteristics of the road being modelled. The direct effects may be summarised as follows:

i. The parameter is set to zero; e.g. cracking is set to zero after an overlay;

ii. The parameter is reset to an absolute value; e.g. the roughness is set to 2 m/km after an overlay;

iii. The parameter is reset using a formula; e.g. the roughness is set as a function of the initial roughness and the thickness of the overlay;

iv. The parameter is not reset; e.g. no changes is set to the width of the pavement after an overlay.

6.7 Evaluating Countermeasure Effects

There are direct and indirect effects of roadwork implementation. Financially, each roadwork activity may directly cost the road agency parts of their road management fund. Physically, roadwork activities may change the road characteristics or road attributes. Whereas, changes to road characteristics or road attributes may indirectly enhance road performance and the road safety level. Therefore, it is necessary that every cost spent on roadwork implementation contributes to a significant benefit and both the cost and the benefit could be quantified wherever and whenever possible.

Robinson et al. (1998) summarised that roadwork implementation will affect the level of service, socio-economic, road user costs, road safety costs, environmental degradation and road administration costs. For quite some times, most of these effects may be quantified using the available road management appraisal. However, there are no robust models to evaluate the benefits in terms of road safety during that period. Therefore, the use of road safety management tools may provide an option to evaluate the impact of roadwork implementation in terms of a road safety benefit.

6.7.1 Sensitivity Analysis

From **Eq. 6.2,** the magnitude of the road safety rating increment due to countermeasure effects, $dRSR_{CE}$, or actually will be better known as countermeasure effects, can be calculated. It is necessary to carry out a sensitivity analysis to evaluate the magnitude of countermeasure effects in terms of Star Rating Score (SRS) followed by the iRAP's Star Rating to identify the classification index of countermeasure effects. The classification of each countermeasure in the Countermeasure Effects Index (CEI) will establish the Countermeasure Effects model that will be used in the overall analytical framework of this research.

One of the problem to evaluate the countermeasure effects is that the implementation of the roadwork activities may be carried out as several complementary activities to the principal work (Morosiuk et al., 2004). Most of the development and upgrading works such as duplication or additional lane may include several other roadwork features such as formation, pavement, shoulder, median, drainage, road furniture and utility relocation. Consequently, the countermeasure effects will depend on the scope of work involved.

It will be hard to assess the exact Star Rating Score (SRS) without knowing the actual scope of work. For example, the development and upgrading work may be subjective to the road safety evaluation as they vary in terms of the scope of work involved. Therefore, it is necessary to assess this variation of all related countermeasures to establish the Countermeasure Effects model.

For this purpose, the evaluation procedure to carry out the sensitivity analysis is suggested as follows:

i. Identify the critical iRAP Road Attribute Risk Factors that contribute to the Star Rating Score (SRS). This can be done by listing down all the possible road attributes and all their risk factors;

ii. Identify the standard deviation (σ) of the road attribute risk factors;

iii. Identify the weightage of all road attributes to assign a ranking of the road attributes based on their sensitivity to Star Rating Score;

iv. Identify the scope of work for each countermeasure and the total value of weighted risk factor to classify the countermeasure classifications;

v. Classify and rank the countermeasures.

The result of the sensitivity analysis as shown in **Table 6.5** and **Table 6.6** respectively shows the assessment of the standard deviation (σ) of iRAP Road Attribute Risk Factors and the assessment of weighted risk factor for each related countermeasure. The result of these assessments is also summarised in **Figure 6.3** and **Figure 6.4**.

From **Figure 6.3**, it is shown that the Median Type, Roadside Severity-Object, Intersection Type, Curvature and Skid Resistance/Grip are among the most sensitive road attributes. Median Type appears to be the most critical attribute because of its major contribution in the Star Rating Score for median traversability as derived in **Eq. 4.2**. Median Type has been assigned as the highest risk in the iRAP methodology as it is a key factor that may contribute to a head-on collision which is considered as the worst case (iRAP, 2013g).

Table 6.5 Standard deviation of iRAP road attribute risk factors

Road Attributes	Risk Factor										Sample Size	Mean	Median	Standard Deviation
	1	2	3	4	5	6	7	8	9	10				
Median Type	0.00	2.00	10.00	35.00	77.00	80.00	83.00	90.00	95.00		9	52.44	77.00	40.18
Roadside Severity – Object	9.00	12.00	15.00	30.00	35.00	40.00	45.00	55.00	60.00	90.00	10	39.10	37.50	25.03
Intersection Type	0.00	0.30	0.50	10.00	12.00	13.00	15.00	16.00	23.00		9	9.98	12.00	8.12
Curvature	1.00	1.80	3.50	6.00							4	3.08	2.65	2.21
Skid Resistance / Grip	1.00	1.40	2.00	3.00	5.50						5	2.58	2.00	1.80
Number of Lanes	0.01	0.02	0.50	1.00							4	0.38	0.26	0.47
Property Access Points	1.00	1.10	1.30	2.00							4	1.35	1.20	0.45
Roadside Severity – Distance	0.10	0.35	0.80	1.00							4	0.56	0.58	0.41
Grade	1.00	1.20	1.70								3	1.30	1.20	0.36
Service Road	1.00	1.50									2	1.25	1.25	0.35
Sight Distance Restriction	1.00	1.42									2	1.21	1.21	0.30
Lane Width	1.00	1.20	1.50								3	1.23	1.20	0.25
Operating and Mean Speeds	0.33	0.42	0.50	0.58	0.67	0.75	0.83	0.92	1.00		9	0.67	0.67	0.23
Road Condition	1.00	1.20	1.40								3	1.20	1.20	0.20
Quality of Curve	1.00	1.25									2	1.13	1.13	0.18
Shoulder Rumble Strips	1.00	1.25									2	1.13	1.13	0.18
Speed Management/Traffic Calming	1.00	1.25									2	1.13	1.13	0.18
Vehicle Parking	1.00	1.20	1.33								3	1.18	1.20	0.17
Centreline Rumble Strips	1.00	1.20									2	1.10	1.10	0.14
Delineation	1.00	1.20									2	1.10	1.10	0.14
Intersection Channelisation	1.00	1.20									2	1.10	1.10	0.14
Intersection Quality	1.00	1.20									2	1.10	1.10	0.14
Street Lighting	1.00	1.15									2	1.08	1.08	0.11
Paved Shoulder Width	0.77	0.83	0.95	1.00							4	0.89	0.89	0.11

Table 6.6 Countermeasure Classification Based on Weighted Risk Factor

Risk Attributes	Standard Deviation (σ)	Weightage	Duplication	Realignment - Horizontal	Median Barrier	Lane Widening	Intersection - Roundabout	Additional Lane	Roadside Safety - Barriers	Roadside Safety - Hazard Removal	Intersection - Signalise	Intersection - Turn Lanes (Signalised)	Intersection - Turn Lanes (Unsignalised)	Regulate Roadside Commercial Activity	Road Surface Rehabilitation	Delineation	Rumble Strips	Shoulder Sealing	Parking Improvements	Central Hatching
Median Type	40.18	49.10	1	1	1															
Roadside Severity – Object	25.03	30.58	1	1		1	1	1	1	1										
Intersection Type	8.12	9.92	1	1		1	1	1			1	1	1	1						
Curvature	2.21	2.70	1	1		1														
Skid Resistance / Grip	1.80	2.20	1	1		1	1	1			1	1	1		1					
Number of Lanes	0.47	0.58	1	1		1	1	1			1	1	1							
Property Access Points	0.45	0.55	1	1		1	1				1	1	1							
Roadside Severity – Distance	0.41	0.50	1	1		1	1	1	1	1						1				
Grade	0.36	0.44	1	1																
Service Road	0.35	0.43	1	1																
Sight Distance Restriction	0.30	0.36	1	1		1			1	1										
Lane Width	0.25	0.31	1	1		1		1										1		
Operating and Mean Speeds	0.23	0.28	1	1		1		1						1						
Road Condition	0.20	0.24	1	1		1	1	1			1	1	1		1					

Table 6.6 Countermeasure Classification Based on Weighted Risk Factor (cont'ed)

Risk Attributes	Standard Deviation (σ)	Weightage	Duplication	Realignment - Horizontal	Median Barrier	Lane Widening	Intersection - Roundabout	Additional Lane	Roadside Safety - Barriers	Roadside Safety - Hazard Removal	Intersection - Signalise	Intersection - Turn Lanes (Signalised)	Intersection - Turn Lanes (Unsignalised)	Regulate Roadside Commercial Activity	Road Surface Rehabilitation	Delineation	Rumble Strips	Shoulder Sealing	Parking Improvements	Central Hatching
Quality of Curve	0.18	0.22	1	1																
Shoulder Rumble Strips	0.18	0.22	1	1													1			
Speed Management /Traffic Calming	0.18	0.22	1	1			1				1	1	1							
Vehicle Parking	0.17	0.20	1	1															1	
Centreline Rumble Strips	0.14	0.17	1	1													1			
Delineation	0.14	0.17	1	1		1	1	1			1	1	1		1	1	1			1
Intersection Channelisation	0.14	0.17	1	1		1	1	1			1	1	1							
Intersection Quality	0.14	0.17	1	1			1				1	1	1							
Street Lighting	0.11	0.13	1	1										1						
Paved Shoulder Width	0.11	0.13	1	1		1		1										1		
Total Aggregate	**81.84**	**1.00**	**100.00**	**100.00**	**49.10**	**48.70**	**45.31**	**45.08**	**31.45**	**31.45**	**14.22**	**14.22**	**14.22**	**10.33**	**2.61**	**0.68**	**0.56**	**0.44**	**0.20**	**0.17**

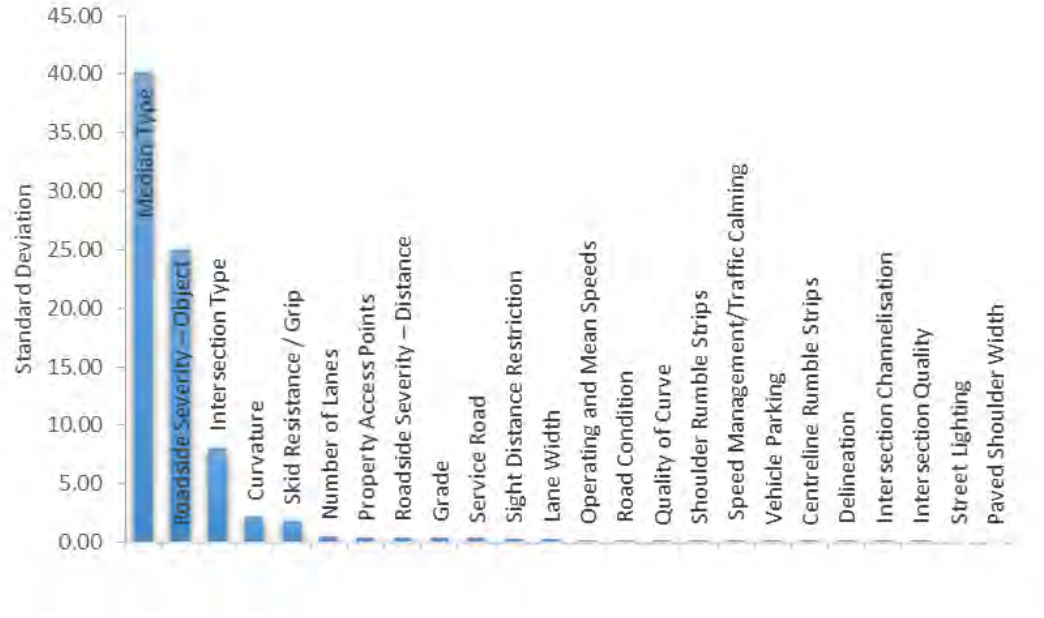


Figure 6.3 Standard deviation of iRAP Road Attribute Risk Factors

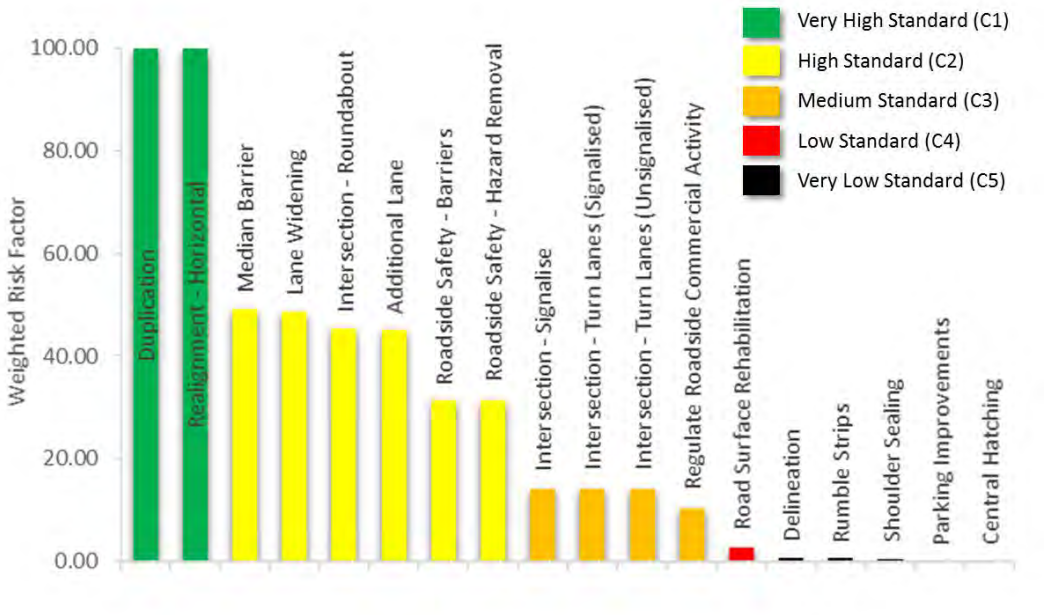


Figure 6.4 Countermeasure classification based on weighted risk factor

In general, the other four most sensitive road attributes which are Roadside Severity-Object, Intersection Type, Curvature and Skid Resistance/Grip may likely contribute to run-off crash type (iRAP, 2013b). The scale of the variation among these attributes shows the risk of crash severity that may be contributed by the respective risk factors. For example, the severity of a crash is determined by the type of object that a vehicle may hit when it runs off from the carriageway even though the cause of the run-off may be contributed by the curvature or skid resistance of the road.

From the evaluation of standard deviation (σ), it may be suggested that the rest of the road attributes are less sensitive to the Star Rating Score. Then, weighting factors are assigned to each road attribute based on the standard deviation (σ) to be used in evaluating the countermeasure classification as shown in **Table 6.6**. **Figure 6.4** shows the countermeasure classification that has been ranked based on the weighted risk factors.

The countermeasure classification has been established from the evaluation of the weighted risk factors calculated based on the total amount contributed by each risk factor. This has been calculated by identifying the risk factors that may affect each countermeasure. Then, the total weighted risk factors are calculated for each countermeasure. The value of weighted risk factors may illustrate the extent of risks that can be reduced or eliminated by each countermeasure. Therefore, the bigger the value, the greater effects that may be contributed by the respective countermeasure.

From **Figure 6.4**, it may be seen that Duplication and Realignment-Horizontal may eliminate the highest possible amount of risk with 100 points. Median Barrier, Lane Widening, Intersection-Roundabout, Additional Lane, Roadside Safety-Barriers and Roadside Safety-Hazard Removal ranging from 31.45 points to 49.10 points follow this. The following range is between 10.33 points to 14.22 contributed by Intersection-Signalise, Intersection-Turn Lanes

(Signalised), Intersection-Turn Lanes (Unsignalised) and Regulate Roadside Commercial Activity. Road Surface Rehabilitation recorded the fourth range with 2.61 points followed by the least range between 0.17 points to 0.68 points for Delineation, Rumble Strips, Shoulder Sealing, Parking Improvements and Central Hatching. The five groups of range recorded by the value of weighted risk factors for each countermeasure may suggest the possible countermeasure classification.

6.8 Proposed Countermeasure Effects Model

From the abovementioned countermeasure classification, it is suggested that the Countermeasure Effects Index (CEI) may be assigned to the groups of range. Based on **Figure 6.4** also, all the countermeasures can be ranked accordingly. **Table 6.7** shows the proposed Countermeasure Effects Index and the countermeasure ranking for the implementation priority of road safety activities.

As this has created the second priority ranking on top of the road management activities ranking, the work activities from road management were consequently integrated into the road safety ranking. The road management activities are intentionally given a higher priority than the road safety activities within the same work type as they offer more specific and comprehensive treatment than road safety appraisal.

Table 6.7 Proposed Countermeasure Effects Index (CEI) and ranking

CE Index	Work Type	Work Activity	[1]Cost Range	Ranking
C1	**Development**	[2]New construction	High	1
		Duplication	High	2
		Realignment-Horizontal	High	3
C2	**Upgrading 1**	Median Barrier	Medium to High	4
		Lane Widening	Medium to High	5
		Intersection-Roundabout	Medium to High	6
		Additional Lane	High	7
		Roadside Safety-Barriers	Medium	8
		Roadside Safety-Hazard Removal	Low to Medium	9
C3	**Upgrading 2**	Intersection-Signalise	Medium	10
		Intersection-Turn Lanes (Signalised)	Low to Medium	11
		Intersection-Turn Lanes (Unsignalised)	Low to Medium	12
		Regulate Roadside Commercial	Low to Medium	13
C4	**Periodic**	[2]Full reconstruction	Medium to High	14
		[2]Strengthening	Medium	15
		[2]Overlay	Low to Medium	16
		Road Surface Rehabilitation	Low to Medium	17
C5	**Routine**	[2]Surface treatment	Low	18
		[2]Pothole patching	Low	19
		Delineation	Low	20
		Rumble Strips	Low	21
		Shoulder Sealing	Medium	22
		Parking Improvements	Low to Medium	23
		Central Hatching	Low	24

[1]Cost Range: Data from iRAP Road Safety Toolkit (iRAP, 2019)

[2]Road management activities to be integrated into the road safety ranking

6.9 Conclusion

This chapter has presented a methodology to develop the Countermeasure Effects model. 15 combinations of possible countermeasure effects have been identified which can be divided into five categories. The category has been recognised as the Countermeasure Effects Index (CEI) which represent the standard and effects of road safety countermeasure calculated based on Star Rating Score (SRS).

To classify all the available countermeasures, a sensitivity analysis has been carried out. The assessment has faced a problem regarding the variation of scope offered by certain countermeasures. Therefore, a statistical standard deviation (σ) analysis has been carried out. From the sensitivity analysis, it is suggested that the variation of countermeasures scope of work has been considered based on the standard deviation (σ) evaluation.

The result from the standard deviation (σ) evaluation has been used to assign the weighting point to evaluate the sensitivity of road attribute risk factors. Later, this weighting point has been used to calculate the weighted risk factors for each countermeasure. This result is vital in identifying the Countermeasure Effects Index (CEI) and the priority ranking for all the countermeasures.

CHAPTER 7

MODEL CONFIGURATIONS

7.1 Introduction

This chapter will present an overview of the data and information about the study area and the selected road network. These data are required as part of the important input in the Road Network Evaluation Tool (RONET) that will be used to evaluate road asset management and roadwork costs element in this research. The data can be divided into two categories which are network information and cost information. The network information consists of general information related to the study area and the selected network including traffic configurations. The cost information consists of the cost components that contribute to total transport costs. All data and information have been gathered from various publications and related public organisations.

7.2 Study Area

The selection of the study area has been influenced by several criteria that it may have such as the following:

i. Availability of road safety data that are appropriate for road safety appraisal;
ii. Significant number from accident statistic;
iii. Significant size of traffic volume and traffic compositions;
iv. Significant amount of road management fund to maintain an appropriate quality of road network;

v. A developing country with a significantly developed road network.

Many countries may fulfil most of the above criteria except they might be lacking in the availability of road safety data that are appropriate for road safety appraisal. In 2007, the International Road Assessment Programme (iRAP) has conducted a pilot study for iRAP road inspections using high-definition multi-view videos. Four countries have been selected for this pilot project to represent the various background of the road environment.

One of the selected countries is Malaysia along with three more countries which are Chile, Costa Rica and South Africa. The inspection in Malaysia has covered approximately 3,688 kilometres of roads, representing approximately 18.6% of the Federal roads in Malaysia or about 5% of Malaysia's paved roads. The inspections included toll-expressways and trunk roads under the responsibility of the Ministry of Works throughout peninsular Malaysia. **Table 7.1** shows the basic characteristics of Malaysia and related information appropriate for this research.

Table 7.1 Basic Characteristics of Study Area

Characteristic	Value
Land area	330,803 sq km
Total population	28.00 million persons
Rural population	15.00 million persons
GDP at current prices	RM1,000.000 billion
Vehicle fleet	15,000,000 vehicles
Total road network length	216,000 km
Total paved roads network length	164,000 km
Diesel roads consumption	350 million litres/year
Gasoline roads consumption	210 million litres/year
Total accidents fatalities	6,900 persons/year
Total accidents serious injuries	4,500 persons/year
Discount rate	12%

(Source: various)

The data that has been collected for the iRAP's pilot study in 2007 will be used for this research. It consists of two toll expressways and ten trunk roads across peninsular Malaysia. These routes were selected based on appropriate criteria in terms of traffic volumes, accident numbers, road geometry and road condition. They represented a various range of different road conditions with high traffic volumes and a significant number of road traffic accidents. **Figure 7.1** shows the map of Peninsular Malaysia with the location of the selected routes. **Table 7.2** shows the selected routes and the approximate length in kilometre.

Table 7.2 Selected routes and the approximate kilometre length

*Route Number	Road Name	Approximate Length (km)	Percentage (%)
E2	Johor Bahru – Kuala Lumpur	335	9.08
E8	Karak - Kuantan	236	6.40
FT1	Alor Setar – Kuala Lumpur	459	12.45
FT2	Gebeng - Karak	208	5.64
FT3	Rantau Panjang – Johor Bahru	725	19.66
FT4	Gerik – Kota Bahru	200	5.42
FT5	Johor Bahru - Ipoh	680	18.44
FT7	Padang Besar – Alor Setar	78	2.11
FT8	Bentong – Sungai Temau	163	4.42
FT67	Sungai Petani - Baling	55	1.49
FT76	Baling - Gerik	54	1.46
TOTAL		**3688**	**100.00**

*E: Expressway FT: Federal Trunk



Figure 7.1 Map of Peninsular Malaysia showing the routes selected for the research

(Source : iRAP, 2009)

7.3 Network Information

As the main objective of this research is to integrate both road management and road safety appraisal models, the condition assessment of both models is carried out by two different models, namely Road Network Evaluation Tools (RONET) and International Road Assessment Programme (iRAP). Both models will respectively be used to evaluate the road condition and road safety levels throughout the selected network. As discussed earlier in **Chapter 4**, most parameters that are used in both assessment models are not compatible with each other. Therefore, both models are required to be configured to ensure they are harmonised throughout the assessment.

7.3.1 Basic Configuration

As the first harmonisation point of both models, the network types used in this research are selected based on the homogeneous road section as explained in **Chapter 5**. The selection of network types based on these characteristics will help in streamlining the classification of roads according to their respective conditions, in terms of road quality and road safety levels. **Table 7.3** shows the characteristics of the network based on their types, terrain, environment and management.

The selected terrain types are also matched with the characteristics of the respective network type. As a country situated on the equator, the environment type of the selected network is per-humid/tropical with an average rainfall of 210 mm per month as commonly received by Malaysia. For the management type, all the selected networks considered for this research are under the management of the Federal government through the Public Works Department.

Table 7.3 Network types

Network Type	Terrain Type	Environment Type	Management Type
Expressway (R6)	Flat	Per-humid / Tropical	Federal
Highway (R5)	Flat	Per-humid / Tropical	Federal
Primary Road (R4)	Hilly	Per-humid / Tropical	Federal
Secondary Road (R3)	Hilly	Per-humid / Tropical	Federal
Minor Road (R2)	Mountainous	Per-humid / Tropical	Federal

The road network is classified into five road condition categories namely Very Good, Good, Fair, Poor and Very poor which represent the range of roughness in terms of International Roughness Index (IRI) as shown in **Table 7.4**. The previous Periodic Maintenance or rehabilitation road work carried out on the respective network section for each condition category is assumed to be between 1 to 20 years. All roads of the selected network are all-weather roads which should be opened throughout the year.

Table 7.4 Road condition classes

Condition Category	Min. Roughness (IRI)	Avg. Roughness (IRI)	Max. Roughness (IRI)	Last Periodic Maintenance (years)	Roads that are Seasonal (%)
Very Good	1.0	2.0	2.5	1	0%
Good	2.5	3.0	3.5	5	0%
Fair	3.5	4.5	5.5	10	0%
Poor	5.5	8.0	10.5	15	0%
Very Poor	10.5	12.0	16.0	20	0%

7.3.2 Traffic Configurations

The default traffic level considered in Road Network Evaluation Tools (RONET) is classified by nine levels namely T1 to T9 (Archondo-Callao, 2009). Based on the homogeneous road sections, the traffic levels appropriate for the selected network are classified within the range as shown in **Table 7.5**. However, in real-time, these traffic levels are not fixed to a certain network type and may vary throughout the entire network.

Table 7.5 Traffic level

Network Type	Traffic Level	Min. Traffic (AADT)	Avg. Traffic (AADT)	Max. Traffic (AADT)
Minor Road (R2)	T7	3,000	6,500	10,000
Secondary Road (R3)	T8	10,000	20,000	30,000
Primary Road (R4)	T8	10,000	20,000	30,000
Highway (R5)	T8	10,000	20,000	30,000
Expressway (R6)	T9	30,000	65,000	100,000

Each traffic level is assigned with a design Structural Number (SN) to represent the pavement strength characteristics associated with the traffic category at the time of construction or last rehabilitation of the road section. The Structural Number values are estimated following the American Association of State Highway & Transportation Officials (AASHTO) guidelines (AASHTO, 1993) as shown in **Figure 7.2**. The Structural Number according to the traffic category as assigned for this research is shown in **Table 7.6**.

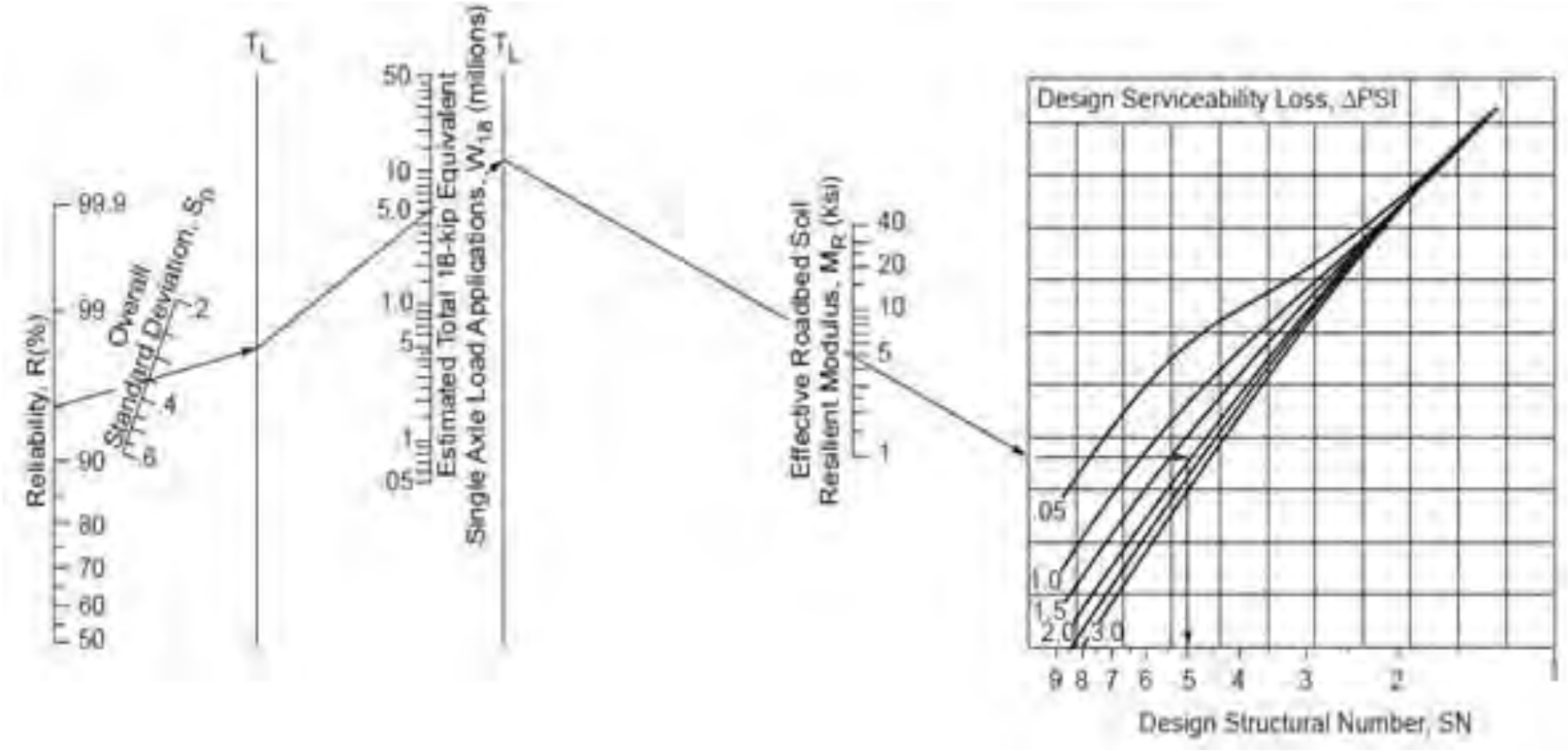


Figure 7.2 AASHTO design chart for flexible pavement

(Source: AASHTO, 1993)

Table 7.6 Design Structural Number appropriate for each traffic category

Traffic Category	Traffic Level	Min. Traffic (AADT)	Avg. Traffic (AADT)	Max. Traffic (AADT)	*Structural Number
Traffic I	T5	300	650	1000	1.5
Traffic II	T6	1000	2000	3000	2.0
Traffic III	T7	3000	6500	10000	3.0
Traffic IV	T8	10000	20000	30000	5.0
Traffic V	T9	30000	65000	100000	8.0

*After AASHTO (1993)

Figure 7.3 shows the yearly 16-hour traffic volume recorded from 2005 to 2014 during the National Traffic Census exercises at 554 census stations on Malaysian roads in Peninsular and East Malaysia. In general, the traffic census shows the annual traffic growth rate about 2.88% within that period with the coefficient of determination (R^2) is 0.9473. However, only a sample of the traffic volume appropriate for the selected network will be considered for this research.

Figure 7.4 shows the vehicle classification based on the traffic census that has been carried out in 2014. The vehicle type classified under this exercise is divided into six categories as the following:

i. Class 1: Motorcars and taxis

ii. Class 2: Small vans and utilities (light 2-axle)

iii. Class 3: Lorries and large vans (heavy 2axle)

iv. Class 4: Lorries with 3-axle (heavy 3-axle or more)

v. Class 5: Buses

vi. Class 6: Motorcycles and scooters

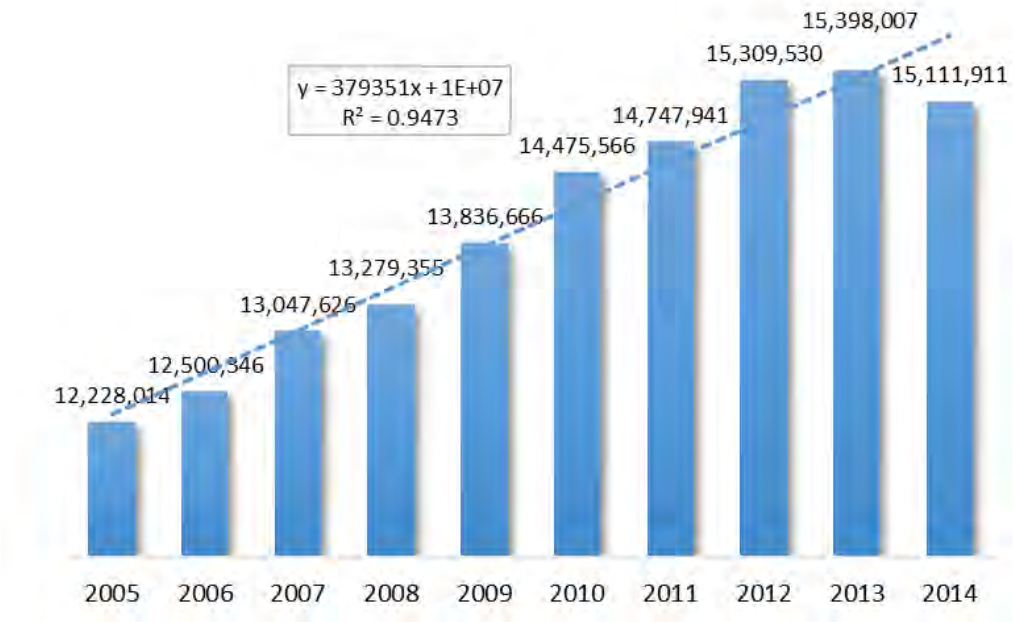


Figure 7.3 Yearly 16-hour traffic volume (2005 - 2014) in Malaysia

(Source: Amended from Pandi et al., 2015)

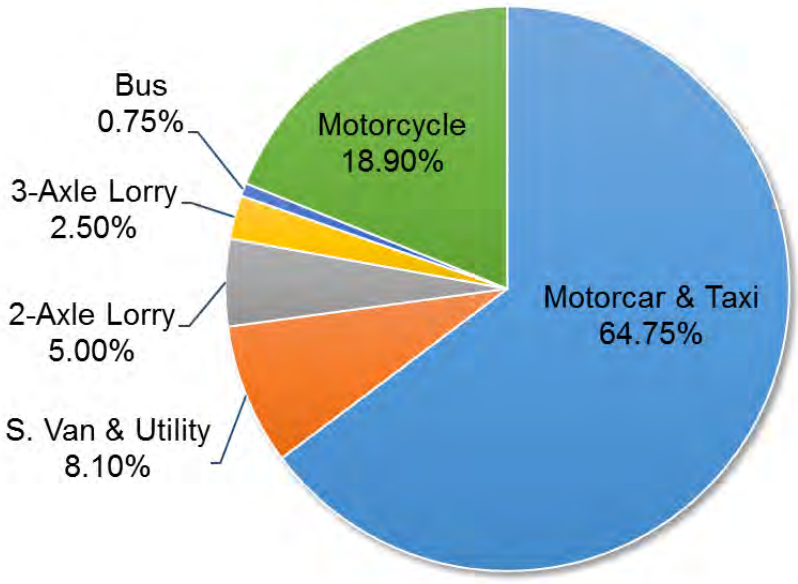


Figure 7.4 Vehicle classification on Malaysian roads

(Source: Amended from Pandi et al., 2015)

Table 7.7 shows the 16-hour traffic recorded from 492 census stations in Peninsular Malaysia. The 16-hour traffic as recorded from 12 states is averaged based on the number of census stations assuming that there is only one point for traffic census station for each state. Therefore, it is assumed that the traffic volume to generate the vehicle fleet configurations is 460,000 vehicles as shown in **Table 7.8**.

Figure 7.5 shows the comparison of traffic configuration between the traffic census and the value that has been used for this research. It is shown that the value opted in this research is comparative and clearly depicted the real composition of traffic in the study area. From the vehicle fleet configurations, the traffic loading characteristics of the network can be determined as shown in **Table 7.9**.

Table 7.7 16-hourly traffic recorded from census station in Peninsular Malaysia

State	Road Length (km)	16-hourly Traffic	No. of Station	Average 16-hourly Traffic
Perlis	1,975.78	193,892	13	14,915
Kedah	12,515.18	1,035,381	52	19,911
Penang	4,248.62	990,548	26	38,098
Perak	26,521.10	1,008,501	69	14,616
Selangor	16,154.28	4,178,834	66	63,316
K. Lumpur	1,531.20	914,498	5	182,900
N. Sembilan	11,816.33	886,514	48	18,469
Melaka	3,310.27	666,627	32	20,832
Johor	21,588.01	2,598,077	75	34,641
Pahang	19,112.79	813,971	45	18,088
Terengganu	8,950.99	442,262	29	15,250
Kelantan	20,617.29	639,085	32	19,971
Total	**148,341.84**	**14,368,190**	**492**	**461,007**

(Source: Amended from Pandi et al., 2015)

Table 7.8 Vehicle fleet configurations

Class	Vehicle Type	Fuel Type (Diesel or Gasoline)	Vehicle Fleet		
			Fleet Composition (%)		Vehicle Fleet (veh)
Class 1	Car (Gasoline)	G	55%	65%	253,000
	Car (Diesel)	D	10%		46,000
Class 2	Utility (Gasoline)	G	3%	6%	13,800
	Utility (Diesel)	D	3%		13,800
Class 3	Truck Light	D	2%	4%	9,200
	Truck Medium	D	2%		9,200
Class 4	Truck Heavy	D	1%	2%	4,600
	Truck Articulated	D	1%		4,600
Class 5	Bus Light	D	1%	3%	4,600
	Bus Medium	D	1%		4,600
	Bus Heavy	D	1%		4,600
Class 6	Motorcycle	G	20%	20%	92,000
Total			**100%**	**100%**	**460,000**

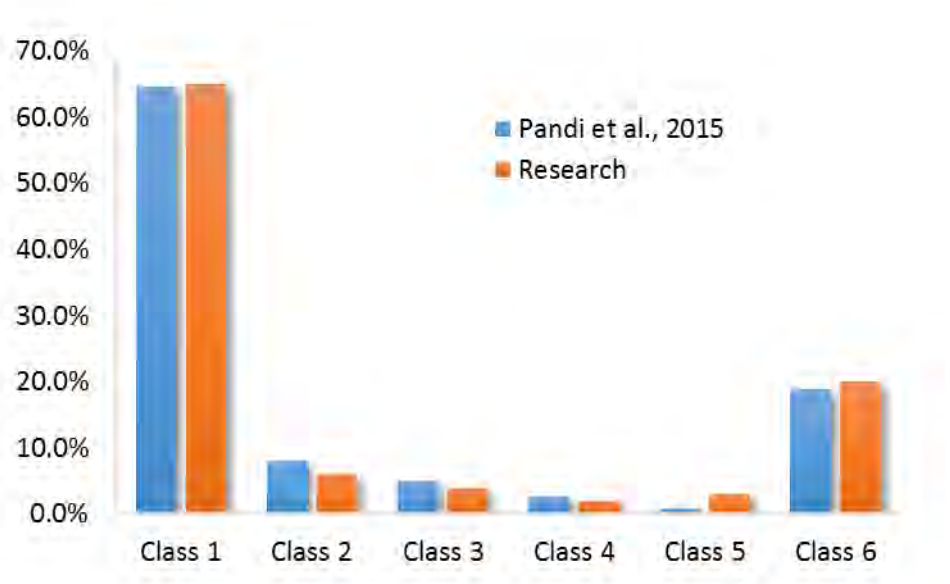


Figure 7.5 Comparison of traffic configuration between traffic census and research

Table 7.9 Traffic loading characteristics

Vehicle Type	Equivalent Standard Axles (ESA/vehicle)	Cargo Payload (Tons/vehicle)	Passengers (persons/vehicle)	Typical Traffic Composition (%)				
				T5	T6	T7	T8	T9
Motorcycle	0.00	0.20	1	20.0%	20.0%	20.0%	20.0%	20.0%
Car Small	0.00	0.30	2	55.0%	55.0%	55.0%	55.0%	55.0%
Car Medium	0.00	0.30	2	10.0%	10.0%	10.0%	10.0%	10.0%
Delivery Vehicle	0.01	0.90	2	3.0%	3.0%	3.0%	3.0%	3.0%
Four-Wheel Drive	0.02	0.80	2	3.0%	3.0%	3.0%	3.0%	3.0%
Truck Light	0.10	2.40	1	2.0%	2.0%	2.0%	2.0%	2.0%
Truck Medium	1.25	5.70	1	2.0%	2.0%	2.0%	2.0%	2.0%
Truck Heavy	2.28	10.60	1	1.0%	1.0%	1.0%	1.0%	1.0%
Truck Articulated	4.63	22.30	1	1.0%	1.0%	1.0%	1.0%	1.0%
Bus Light	0.04	1.25	12	1.0%	1.0%	1.0%	1.0%	1.0%
Bus Medium	0.70	2.50	30	1.0%	1.0%	1.0%	1.0%	1.0%
Bus Heavy	0.80	3.20	40	1.0%	1.0%	1.0%	1.0%	1.0%
Total				**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**
ESA Loading (M ESA/year)				**0.027**	**0.082**	**0.267**	**0.821**	**2.667**
Payload/Vehicle (tons/vehicle)				**0.85**	**0.85**	**0.85**	**0.85**	**0.85**
Passengers/Vehicle (persons/vehicle)				**2.50**	**2.50**	**2.50**	**2.50**	**2.50**

7.4 Costing Components

The main function of a road investment appraisal is to calculate the total transport costs. The components of transport costs are contributed by road agency and road users. The cost implication to the road agency will increase when the standard of roads that they provided increases. Conversely, the cost implication to road users will reduce when the quality of the road increases. Therefore, the road investment appraisal may be used to calculate the optimum transport cost to balance road agency and road user costs. **Figure 7.6** shows the relationship of road agency and road user costs on road standard.

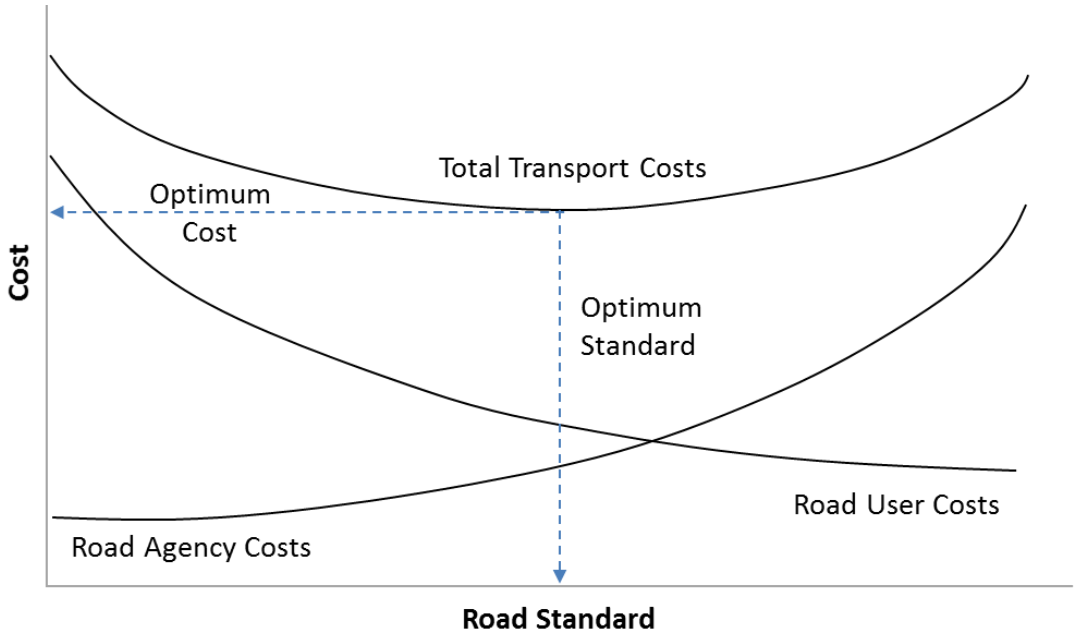


Figure 7.6 Total transport costs

(Source: Amended from Odoki and Kerali, 2000)

The envisaged road investment appraisal that integrates road safety and road management appraisal should be able to calculate the total transport costs in the same manner. To consider

this, the cost of road safety countermeasure implementations is considered as part of the available roadwork options in the road agency costs. This will enable a rational and seamless integration of the investment appraisal during the analysis. The accident costs should remain as part of the component within the road user costs. Therefore, this complies with the essence of the existing principle of total transport costs.

7.4.1 Roadwork Costs

Currently, the implementation of recurrent road maintenance on Federal roads in Malaysia is carried out based on a conventional road maintenance contract. No matter what the condition of the road is, a fixed amount of payment is agreed between contractors and the road agency to carry out seven scopes of maintenance according to agreed performance standard and cycles on the assigned road networks. Only stretches that are included in capital roadworks are excluded from the recurrent maintenance. **Table 7.10** shows the unit costs for recurrent maintenance works.

The capital works on road pavement are carried out according to the condition of roads. Periodic maintenance is carried out on the road in Fair or Good condition with Resurfacing or Preventive Treatment respectively. Strengthening and Reconstruction are carried on the road in Poor or Very Poor condition respectively. New Construction will be proposed for the saturated link within the network. **Table 7.11** shows the unit costs for capital roadworks.

The capital works that tackle road safety issues are generated from the countermeasure list as proposed by the International Road Assessment Programme (iRAP) pilot study. The list is arranged according to the Countermeasure Effects Index (CEI) ranking as discussed in **Chapter 6**. **Table 7.12** shows the unit costs for recurrent maintenance works, capital

roadworks and road safety countermeasures. As RONET works with a two-lane equivalent road class, the financial unit costs used in this research are two-lane unit cost.

Table 7.10 Recurrent maintenance works unit costs

Current Condition	Scope of Work	Cycles	Annual Unit Costs (MYR/km)
All conditions: i. Very Good ii. Good iii. Fair iv. Poor v. Very Poor	R01 – Pothole/crack sealing	When required	MYR20,400 per km per year
	R02 – Shoulder sealing	When required	
	R03 – Grass cutting	12 cycles/year	
	R04 – Furniture cleaning	2 cycles/year	
	R05 – Bridge and culvert cleaning	1 cycles/year	
	R06 – Roadline repainting	2 years/cycle	
	R07 – Drainage cleaning	1 cycle/year	

(Source: Amended from Harun, 2012)

Table 7.11 Capital roadworks unit costs

Current Condition	Road Work Type	Unit Costs (MYR/km)	Remarks
Good	Preventive Treatment	20,400	Cost per km/year
Fair	Resurfacing (Overlay)	200,000	Thickness = 50 mm
Poor	Strengthening (Overlay)	300,000	Thickness = 100 mm
Very Poor	Reconstruction	400,000	*SN = 3, IRI : 2.0
No Road	New Construction	2,000,000	-

*SN: Structural Number IRI: International Roughness Index

Table 7.12 Road safety countermeasures unit costs

Countermeasure Types	Unit	Length or number of sites	Estimated Cost for 20 years (MYR 'mil)	Unit Cost (MYR/km)
*New construction	km			2,000,000
Duplication (additional lanes)	km	120	220	1,833,000
Realignment - horizontal	km	3	1	333,000
Median barrier	km	40	20	500,000
Lane widening	km	30	6	200,000
Intersection - roundabout	sites	20	3	150,000
Additional lane	km	380	179	471,000
Roadside safety - barriers	km	30	9	300,000
Roadside safety - hazard removal	km	1650	24	15,000
Intersection - signalise	sites	190	25	132,000
Intersection - turn (signalised site)	sites	60	4	67,000
Intersection - turn (unsignalised site)	sites	120	14	117,000
Regulate roadside commercial activity	km	0.2	0.03	150,000
*Full reconstruction	km			400,000
*Strengthening	km			300,000
*Overlay	km			200,000
Road surface upgrade	km	10	0.8	80,000
*Surface treatment	km			80,000
*Pothole patching	km			20,400
Improve delineation	km	130	11	85,000
Rumble strip / flexi-post	km	10	0.5	50,000
Shoulder widening	km	270	34	126,000
Parking improvements	km	0.1	0.02	200,000
Central hatching	km	10	0.4	40,000
**Pedestrian footpath	km	10	2	200,000
**Pedestrian crossing	sites	130	13	100,000
**Motorcycle lanes	km	270	17	63,000
**Bicycle facilities on or off road	km	1	0.03	43,000
TOTAL		**3484**	**583.78**	

* Road management activities to be integrated into the road safety ranking

**Countermeasures that are not considered in this research

(Source: Amended from iRAP, 2009)

7.4.2 Road User Costs

Three aspects that normally included as road user costs are as follows (Robinson et al., 1998):

i. Vehicle operating costs: such as fuel, maintenance and wear and tear;

ii. Time costs: such as delays due to congestion or disruption;

iii. Road accident costs: such as medical costs, vehicle and asset repair costs.

The above aspects are interrelated to each other as they are highly dependent on the road condition, road environment and traffic condition. For example, number and type of vehicles, geometry and alignment, road surface condition, skid resistance, speed limit and junctions quality are among the factors that may influence the vehicle operating costs, time costs and road accident costs. With slight changes to one of these factors, it may affect a significant change to one of the road user costs aspects.

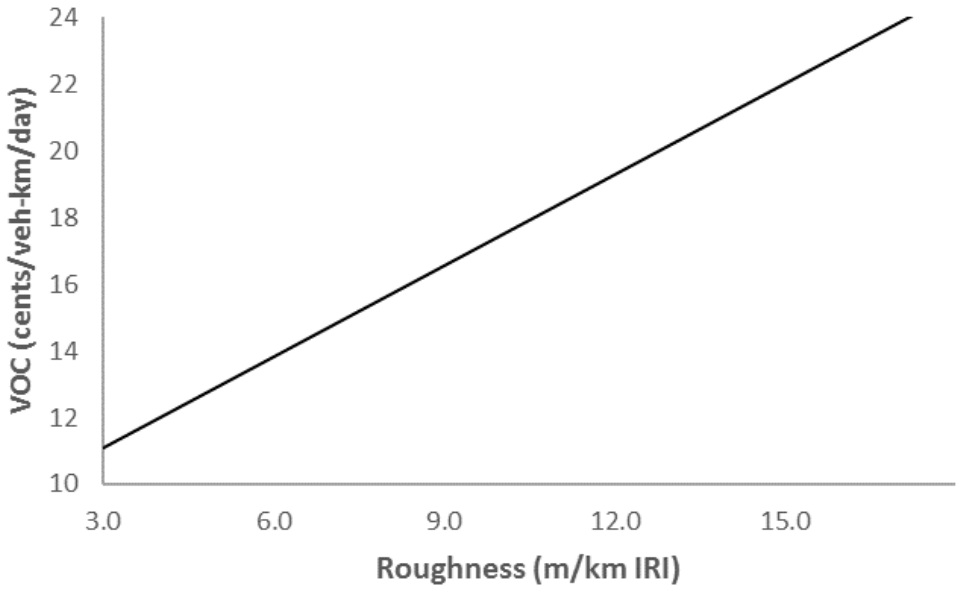


Figure 7.7 Indicative vehicle operating costs for different roughness values

(Source: Amended from Robinson, 2008)

Road condition has a significant relationship with road user costs as they may significantly affect the road user costs especially the vehicle operating costs and time costs components. Robinson (2008) claimed that the vehicle operating costs are strongly correlated to road roughness as shown in **Figure 7.7**. Therefore, the vehicle operating costs can be estimated based on the value of roughness if the relationship between both parameters has been established. For example, in **Figure 7.7**, vehicle operating costs may be calculated based on the regression equation, VOC = 11.1 + 0.83R.

Using the same principle, Archondo-Callao (2009) suggested that the road user costs relationship to roughness can be defined in the form of a cubic polynomial as shown in the following equation:

$$\textit{Unit Road User Costs} = a_0 + a_1 * IRI + a_2 * IRI^2 + a_3 * IRI^3 \quad \textbf{(7.1)}$$

where,

Unit Road User Costs	=	the unit road user costs of the vehicle fleet
IRI	=	the roughness of the road (m/km)
a_0, a_1, a_2 and a_3	=	the coefficients of the cubic polynomial

The coefficients of the cubic polynomial for each traffic level can be computed to suit local condition using the Road User Costs Knowledge System (RUCKS) provided by the World Bank.

Table 7.13 shows the default values of the coefficients of the cubic polynomial to calculate the unit road user costs as proposed by RONET. The coefficients are computed as the financial

cost which includes taxes and subsidies to reflect the actual market costs users' conversion preferences. For this research, the default values will be used for the coefficients of the cubic polynomial as they reflect the condition in most developing countries.

Table 7.13 The coefficients of the cubic polynomial for the unit road user costs

Coefficient	Traffic Level				
	T5	**T6**	**T7**	**T8**	**T9**
a_0	0.28871	0.28871	0.28840	0.27267	0.41310
a_1	-0.00055	-0.00055	-0.00060	-0.00222	0.00613
a_2	0.00148	0.00148	0.00151	0.00173	0.00049
a_3	-0.00003	-0.00003	-0.00003	-0.00004	-0.00002

(Source: Amended from Archondo-Callao, 2009)

7.4.3 Road Accident Costs

Jacobs (1995) highlighted several workable methods and approaches that can be used to evaluate the unit cost of a road accident as presented in **Chapter 2**. Each method produces a considerably different value of accident costs due to nature and the purpose of the costing. Therefore, it might be impossible to get an objective and accurate road accident costs that are comparable and applicable to both developed and developing countries.

In 1995, the Transport Research Laboratory (TRL) claimed that a series of road safety studies have been carried out in developing countries to predict changes in accident rates following modifications in road design (Bennett and Greenwood, 2003). The result of these studies showed that limited correlation was found between variables, analysis methods and models. Furthermore, the gap in the fatality rate between developed and developing countries is so wide

due to the nature of the traffic and environment of the roads. Therefore, it was suggested that a series of "look-up tables" based on the accident group in terms of accident rate per 100 million vehicle-km is used to generalise the annual number of accidents.

From Odoki and Kerali (2000), the annual road accident costs (Ac_{cost}) are given by the following equations:

$$Ac_{cost} = Ac_{rate\text{-}y} \; x \; Unit\ Cost \quad \textbf{(7.2)}$$

$$Ac_{rate\text{-}y} = Exposure \; x \; Ac_{rate} \quad \textbf{(7.3)}$$

where:

$Ac_{rate\text{-}y}$ = the annual number of accidents

Unit Cost = the unit cost of accident

Exposure = the annual exposure to accidents (section/intersection)

For section, $Exposure_{sec} = \dfrac{365 \times AADT \times section\ length}{10^8}$ **(7.4)**

For intersection, $Exposure_{int} = \dfrac{365 \times AADT}{10^8}$ **(7.5)**

Ac_{rate} = the accident rate per 100 million veh-km

The above accident rate (Ac_{rate}) terminology can be defined as the average number of reported annual accidents ($Ac_{rate\text{-}y}$), which should be measured over a period of time (for example, 5 years), divided by the annual exposure to accidents as derived in the following equation:

$$Ac_{rate} = \frac{Ac_{rate\text{-}y}}{Exposure} \quad \textbf{(7.6)}$$

Table 7.14 shows the 5-year accident rate in Malaysia as recorded from 2011 to 2015 and **Table 7.15** shows the number of fatalities and serious injuries per 100 million vehicle-km as averaged from the 5-year accident rate. **Appendix 7** shows the road accident statistics in Malaysia from 1997 to 2015.

Table 7.14 5-year accident rate in Malaysia as recorded from 2011 to 2015

Year	Registered Vehicles	Population	Road Crashes	Road Deaths	Road Injury	Death per 100 mil' VKT	Injury per 100 mil' VKT
2011	21,401,269	29,000,000	449,040	6,877	18,693	146.8	399.0
2012	22,702,221	29,300,000	462,423	6,917	17,522	133.5	338.2
2013	23,819,256	29,947,600	477,204	6,915	12,985	121.9	228.9
2014	25,101,192	30,300,000	476,196	6,674	13,030	106.4	207.7
2015	26,301,952	31,190,000	489,606	6,706	11,552	96.0	165.4
5-year Average	**23,865,178**	**29,947,520**	**470,894**	**6,818**	**14,756**	**120.92**	**267.8**

(Source: Amended from PDRM, 2017)

Table 7.15 Number of fatalities and serious injuries per 100 million vehicle-km

Accident Type	Expressway (R6)	Highway (R5)	Primary (U4)	Secondary (R3)	Minor (R2)	Total
Fatalities	15	25	25	50	5	120
Injuries	30	50	50	125	15	270

(Source: Amended from PDRM, 2017)

There are some practical problems faced by developing countries to estimate the accident cost as it requires intensive study which is costly and time-consuming. Therefore, McMahon and Dahdah (2008) have suggested that an alternative approach to estimate road accident costs. The so-called ‘rule-of-thumb’ approach has been investigated to relate the Value of Statistical Life (VSL) to GDP per capita for both developed and developing countries.

McMahon and Dahdah concluded that the value of fatality (VOF) is between 60 to 80 times Gross Domestic Product (GDP) per capita and the value of injury (VOI) is between 20 to 30 per cent of the value of fatality. The value of fatality and injury as suggested by McMahon and Dahdah are as shown in the following equations:

$$\textit{Value of Fatality (VOF)} = f\text{*GDP/Capita} \quad (60 < f < 80) \qquad \textbf{(7.7)}$$

$$\textit{Value of Injury (VOI)} = i\text{*VOF} \quad (20 < i < 30) \qquad \textbf{(7.8)}$$

Considering Malaysia as the country within the central limit of the value, based on **Eq. 7.7** and **Eq. 7.8**, the value of fatality and injury accident costs are estimated as shown in **Table 7.16**.

Table 7.16 The value of fatality and injury accident costs

Factor to multiply GDP per capita, *f*	Serious injuries cost percentage, *i*	Accident cost (MYR)	
		Fatalities	Serious injuries
70	25%	2,500,000	625,000

7.5 Conclusion

This chapter has presented an overview of the information about the study area and the selected road network. Basis of the information has been presented to ensure that the data to be used in this research is validated. The information that has been presented will be used to configure the systems that will be used for analysis in this research. It has been presented in a manner that is

friendly to Road Network Evaluation Tools (RONET) so it will be easy to input the information throughout the analysis of this research.

CHAPTER 8

PRELIMINARY CONDITION ASSESSMENT

8.1 Introduction

This chapter will present the findings from the data collection that has been carried out for this research. Generally, there are two groups of data needed in this study, which are appropriate for application in road management and road safety appraisal, to demonstrate the integration of both appraisal models. This chapter will present the background of the data collection to fulfil the requirements of the two models that are used. The findings from the data collection will be presented in a manner that they are going to be used for both appraisal models and the demonstration of the integrated model.

8.2 Overview of Data Collection

Data collection related to road inventory and pavement condition which is appropriate for this research will require the most detailed and comprehensive information quality level (IQL) as proposed by the World Bank (Robinson et al., 1998). Data that fulfil this information quality level are normally collected using high-speed survey equipment carried out by survey organisation. **Figure 8.1** shows the example of a high-speed survey vehicle equipped with a multi-laser profiler, a global positioning system (GPS) and a digital imaging system.



Figure 8.1 Ikram Road Scanner (IRS)

(Source: Kumpulan Ikram Sdn Bhd)

The data collection process for this research has faced a major challenge due to the cost of getting fresh data which is very high. Therefore, it has been decided that the required data is gathered from the available resources such as the respective road authority at a minimal cost. However, readily available data may not be hindered from any shortcoming as they are not specifically designed for this research. Slight modification needs to be done to ensure the compatibility of the data.

As the available data has been previously collected for a different objective, they may not be synchronised in terms of location and coverage. Some stretches of road may have both road management data and road safety data appropriate for this research. However, some stretches of road may have road management data and may not have any road safety data or vice versa or even without both categories of data at all.

There are four possible scenarios that the available data for road management and road safety appraisal that may appear in a road network as shown in **Table 8.1**. Therefore, artificial data

need to be considered to complement the lack of data. Data mining will be carried out to present the process of generating artificial data to complement the lack of data. However, locations without any data will not be considered to avoid any ambiguity.

Table 8.1 Available data scenario

Category	Road Safety	Road Management	Remarks
Type I	✓	✓	To use real data
Type II	✓	✗	To use artificial road management data
Type III	✗	✓	To use artificial road safety data
Type IV	✗	✗	Not to be considered

Legends: ✓ Available ✗ Not Available

8.3 Observed Condition Assessment

In general, two types of data will be required to carry out the analysis for this research. These data are comprised of road network condition and road safety condition which respectively articulate the information with regards to road surface quality and road safety level of the network. Therefore, both data are essential to be used to demonstrate the long-term impact of integrating road management and road safety appraisal.

Currently, it is common that most developing countries may not be able to provide the data for both road management and road safety information on the same network. It is essential to provide a solution to tackle this issue so that this methodology may work for most countries. Therefore, this research will generate data that fulfil the data condition as mentioned in **Table 8.1**.

8.3.1 Validation of Road Safety Degradation Model from Type I Data

Like most countries, data that provides the road safety level information in Malaysia is also not as easily available as the road condition data. To meet the research requirement, the road safety level data that has been collected from the International Road Assessment Programme (iRAP) pilot study in 2007 will be used as the basis of the study area network for this research. The same road network will be used to get the appropriate road condition data. From the iRAP pilot study, the existing road safety level for vehicle occupants in terms of iRAP Star Rating is summarised in **Table 8.2**.

Table 8.2 Selected network Star Rating (Vehicle Occupants)

Star Rating	Length (km)	Percentage
★★★★★	1	0.03%
☆☆☆☆	1163	31.53%
★★★	953	25.84%
★★	1127	30.56%
★	444	12.04%
Total	**3688**	**100%**

(Source: Amended from iRAP, 2009)

For the road condition data, survey data from the annual assessment of Federal Trunk Roads on the existing pavement condition will be used. The data collection has been carried out in 2010 by Kumpulan Ikram Sdn Bhd (KISB) appointed by the Public Works Department of Malaysia (JKR). The existing road condition in terms of the International Roughness Index (IRI) is summarised in **Table 8.3**. Based on the common pavement deterioration rate, a difference of 4 years is considered a valid comparison, between 4 to 8 years is a poor comparison and beyond that period is an invalid comparison.

Table 8.3 Selected network roughness index (IRI)

Roughness (IRI)	Length (km)	Percentage
Very Good	458	12.42%
Good	916	24.83%
Fair	1638	44.42%
Poor	430	11.67%
Very Poor	246	6.67%
Total	**3688**	**100%**

(Source: Amended from KISB, 2011)

A comparison of road safety level and road condition percentage based on their respective ratings is shown in **Figure 8.2**. Details of the distribution of the road safety ratings are shown in **Table 8.4**. Details of the distribution of the road condition are shown in **Table 8.5**.

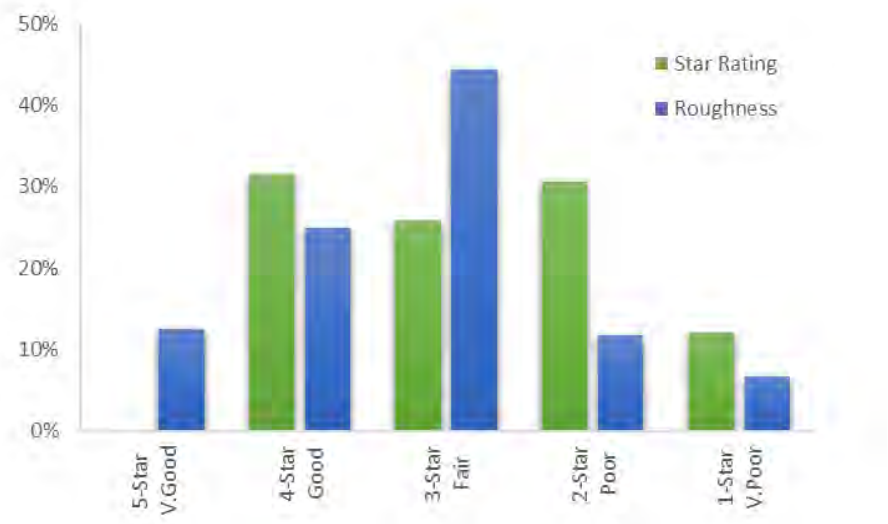


Figure 8.2 Comparison of road safety level and road condition percentage

Table 8.4 Selected network and distribution of Star Rating (Vehicle Occupants)

Route Number / Road Name	Traffic	Approximate Length		Star Rating (km)				
		km	%	★	★★	★★★	★★★★	★★★★★
E1 Kuala Lumpur - Bkt. Kayu Hitam	70000	495	13.42			80	415	
E2 Johor Bahru - Kuala Lumpur	60000	335	9.08			62	273	
E8 Karak - Kuantan	40000	236	6.40	5		5	225	1
Expressway (R6)	**170000**	**1066**	**28.90**	**5**	**0**	**147**	**913**	**1**
F1 Alor Setar - Kuala Lumpur	25000	459	12.45	30	270	110	49	
F3 Rantau Panjang - Johor Bahru	25000	725	19.66	59	324	292	50	
Highway (R5)	**50000**	**1184**	**32.10**	**89**	**594**	**402**	**99**	**0**
F5 Johor Bahru - Ipoh	20000	680	18.44	70	270	240	100	
F2 Gebeng - Karak	20000	208	5.64	60	70	60	18	
Primary (R4)	**40000**	**888**	**24.10**	**130**	**340**	**300**	**118**	**0**
F7 Padang Besar - Alor Setar	15000	78	2.11	15	58	5		
F4 Gerik - Kota Bahru	10000	200	5.42	100	70	30		
F8 Bentong - Sungai Temau	10000	163	4.42	50	20	60	33	
Secondary (R3)	**35000**	**441**	**12.00**	**165**	**148**	**95**	**33**	**0**
F67 Sungai Petani - Baling	7500	55	1.49	30	20	5		
F76 Baling - Gerik	7500	54	1.46	25	25	4		
Minor (R2)	**15000**	**109**	**3.00**	**55**	**45**	**9**	**0**	**0**
TOTAL	**310000**	**3688**	**100.0**	**444**	**1127**	**953**	**1163**	**1**

Table 8.5 Selected network and distribution of roughness index (IRI)

Route Number / Road Name	Traffic	Approximate Length		Roughness (IRI-km)				
		km	%	V. Poor	Poor	Fair	Good	V. Good
E1 Kuala Lumpur - Bkt. Kayu Hitam	70000	495	13.40		5	170	200	120
E2 Johor Bahru - Kuala Lumpur	60000	335	9.10		10	85	150	90
E8 Karak - Kuantan	40000	236	6.40	5	15	38	106	72
Expressway (R6)	**170000**	**1066**	**28.90**	**5**	**30**	**293**	**456**	**282**
F1 Alor Setar - Kuala Lumpur	25000	459	12.50	15	65	210	111	58
F3 Rantau Panjang - Johor Bahru	25000	725	19.70	75	95	425	90	40
Highway (R5)	**50000**	**1184**	**32.10**	**90**	**160**	**635**	**201**	**98**
F5 Johor Bahru - Ipoh	20000	680	18.40	60	65	360	130	65
F2 Gebeng - Karak	20000	208	5.60	16	45	105	36	6
Primary (R4)	**40000**	**888**	**24.10**	**76**	**110**	**465**	**166**	**71**
F7 Padang Besar - Alor Setar	15000	78	2.10	10	20	30	14	4
F4 Gerik - Kota Bahru	10000	200	5.40	35	45	80	40	
F8 Bentong - Sungai Temau	10000	163	4.40	20	40	70	30	3
Secondary (R3)	**35000**	**441**	**12.00**	**65**	**105**	**180**	**84**	**7**
F67 Sungai Petani - Baling	7500	55	1.50	5	10	35	5	
F76 Baling - Gerik	7500	54	1.50	5	15	30	4	
Minor (R2)	**15000**	**109**	**3.00**	**10**	**25**	**65**	**9**	**0**
TOTAL	**310000**	**3688**	**100.0**	**246**	**430**	**1638**	**916**	**458**

The correlation between road safety data from **Table 8.4** and road condition data from **Table 8.5** may be calculated by the square of the Pearson Product-Moment Correlation Coefficient, *r*, which measures the correlation or linear association between two sets of variables. The Pearson Product-Moment Correlation Coefficient is given by the following formula (Jackson, 2015):

$$\boldsymbol{r = \frac{\sum(x-\bar{x})(y-\bar{y})}{\sqrt{\sum(x-\bar{x})^2 \sum(y-\bar{y})^2}}} \qquad \textbf{(8.1)}$$

where $\bar{x}$ and $\bar{y}$ are the sample means of the two sets of variables.

The equivalent Star Ratings and roughness for each road network type are paired to test the correlation between road safety and road condition. The RSQ function in Microsoft Excel is used to calculate the coefficient of determination, R^2. The value of R^2 can vary between 0 and 1, where $R^2 = 1$ indicates that the two variables fit the model with perfect correlation while $R^2 = 0$ means that there is no linear relationship between the two variables. The result of the correlation between the equivalent pair of Star Ratings and roughness are shown in **Figure 8.3** to **Figure 8.7**.

Table 8.6 shows the correlation summary between road safety and road condition. From this analysis, only the coefficient of determination (R^2) between 3-Star and Fair condition pairing significantly correlate to each other with a value of more than 90%. However, the combination of Poor/Very Poor and Good/Very Good with their respective Star Rating as shown by the orange data and trendlines in **Figure 8.4** and **Figure 8.6** have significantly increased the correlation between the two parameters with a value of more than 90%.

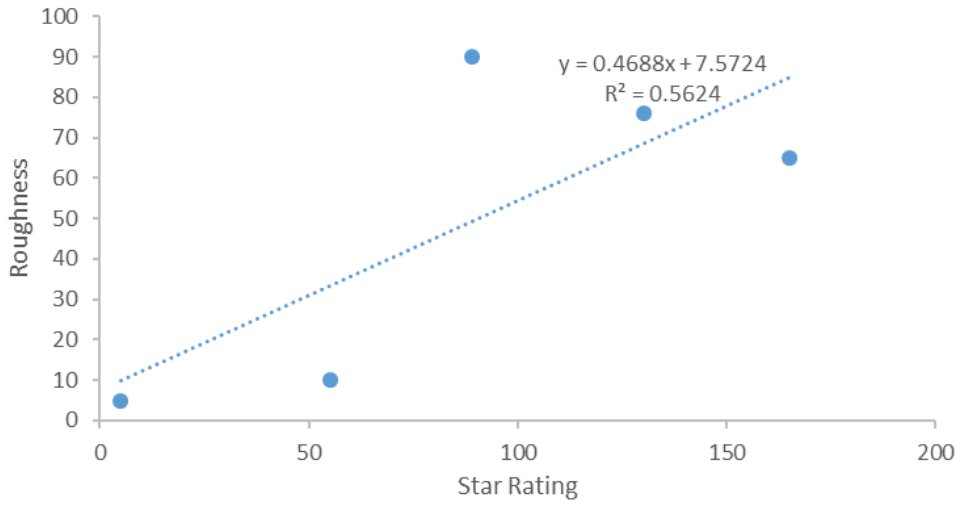


Figure 8.3 Correlation between 1-Star road safety and Very Poor road condition

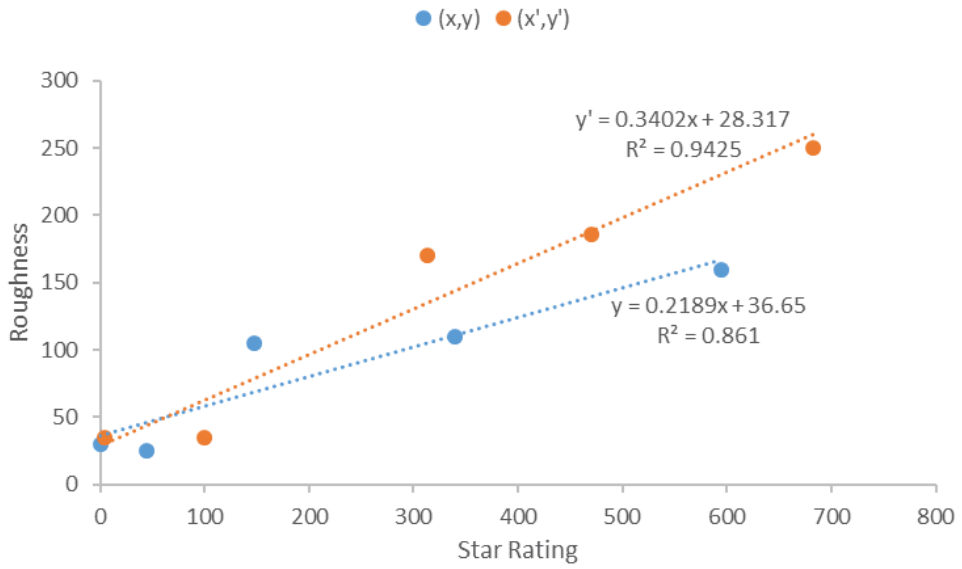


Figure 8.4 Correlation between 2-Star road safety and Poor road condition

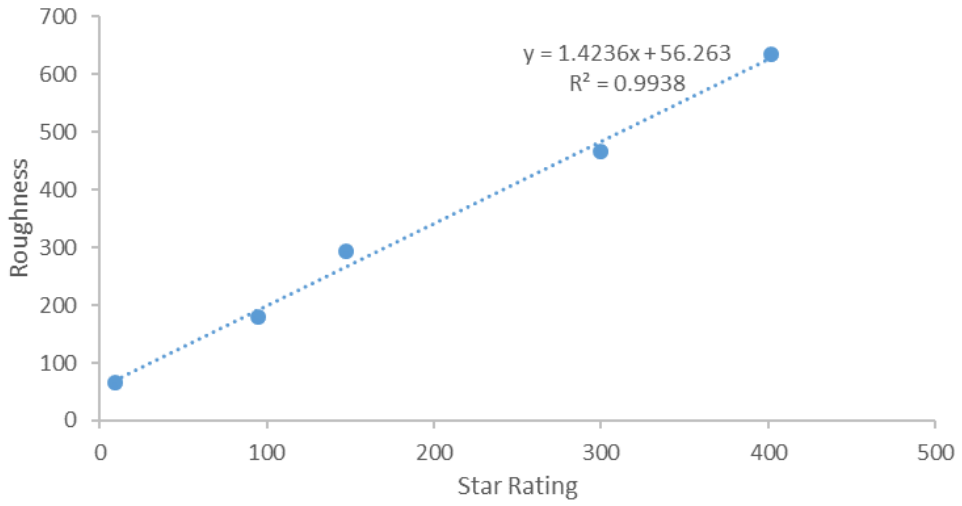


Figure 8.5 Correlation between 3-Star road safety and Fair road condition

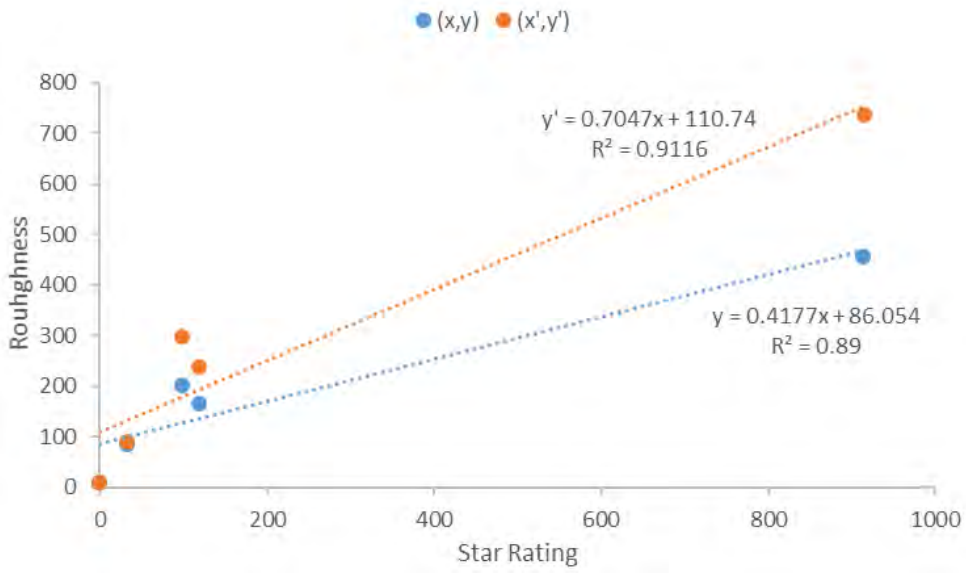


Figure 8.6 Correlation between 4-Star road safety and Good road condition

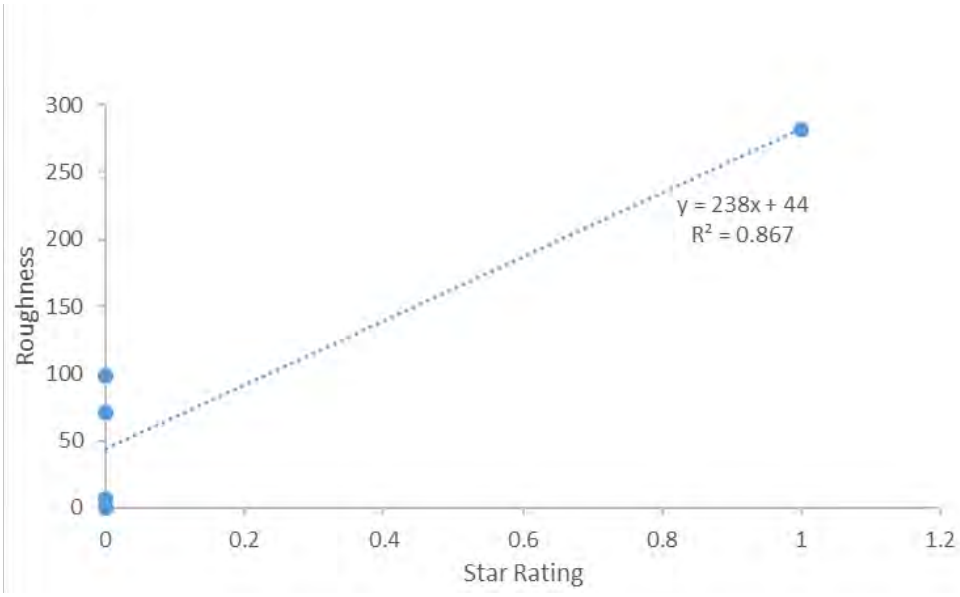


Figure 8.7 Correlation between 5-Star road safety and Very Good road condition

Table 8.6 Correlation summary between road safety and road condition

***x* = Star Rating**	***y* = Roughness**	R^2	***(x', y')***	R'^2
★	Very Poor	0.5624	Poor	0.9425
★★	Poor	0.8610		
★★★	Fair	0.9938	Fair	0.9938
★★★★	Good	0.8900	Good	0.9116
★★★★★	Very Good	0.8670		

Therefore, it is suggested that a transition to the road condition classification from five categories (x,y) to just three categories (x',y') may increase the correlation between the road safety rating and roughness. In this case, the 1-Star and 2-Star roads with their respective roughness conditions of Poor and Very Poor will be combined as Poor category while the of 4-Star and 5-Star roads with their respective roughness conditions of Good and Very Good will

be combined as Good category. This has significantly increased the correlation between the two parameters with a value of more than 90% as shown in **Table 8.6**. In addition, it may be suggested that the total length of road within the transition category of road safety and roughness (Poor and Good) are shared between their respective category combinations.

8.4 Generation of Road Condition and Road Safety Data

In case one of the road safety or road condition data is not available in some countries, it may be feasible to apply a data generation process to replace missing data with substituted values (Gelman & Hill, 2006). Therefore, unavailable data can be generated based on the relationship between road safety degradation and roughness progression.

In **Chapter 5**, it has been presented that the road condition may be represented by roughness in terms of the International Roughness Index (IRI), which is highly correlated with the area of cracking observed on the pavement surface as claimed by Morosiuk et al. (2004). It has also been established that the International Road Assessment Programme (iRAP) methodology may predict road safety degradation relative to roughness in a similar manner. The deterioration in road condition may be presented by the Road Condition and Skid Resistance/Grip attributes in the iRAP model to simulate the road safety degradation.

Therefore, the relationship between road safety degradation and roughness progression may be established by combining the cracking progression model and the road safety degradation progression phases as shown in **Figure 4.4** and **Figure 5.3** respectively. **Figure 8.8** shows the combination of the cracking progression and the road safety degradation progression model that forms the relationship between road safety level and road condition. From **Figure 8.8**, the road condition classification may be established from the roughness relationship relative to the affected area as summarised in **Table 8.7**.

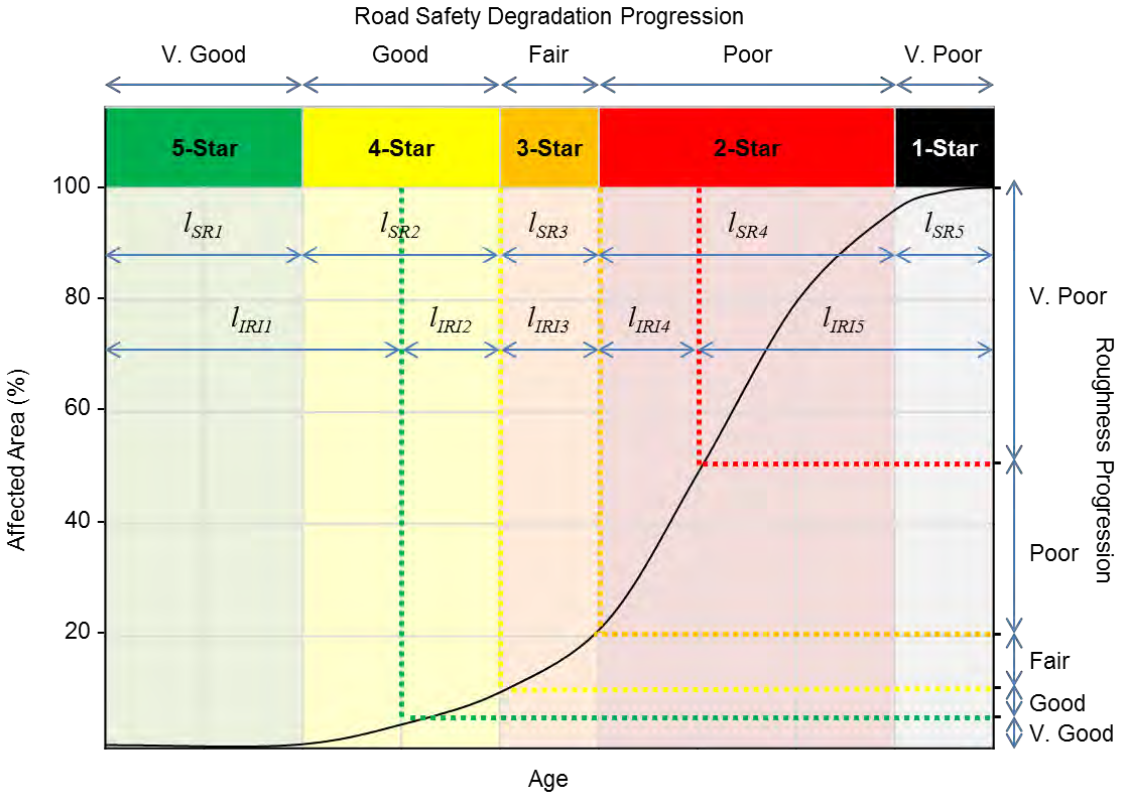


Figure 8.8 Relationship of road safety rating (iRAP) and road roughness (IRI)

Table 8.7 Roughness classification based on the affected area

Road Condition (IRI)	Affected Area (%)
Very Good	0 – 5
Good	5 – 10
Fair	10 – 20
Poor	20 – 50
Very Poor	50 – 100

For road safety degradation, the progression is made of nine possible combinations (3 x 3 values) between two road attributes which are Road Condition and Skid Resistance/Grip which has been calculated based on their Star Rating Score (SRS). Considering the condition state of road safety degradation change vector as shown in **Table 5.11**, it may be assumed that road

safety degradation progress gradually over time or age of pavement. Therefore, the proportion of road safety star rating classification as presented in **Figure 8.8** may be used to represent the progress of the affected area.

As presented in **Table 8.6**, it may be assumed that the total length of road in Fair road condition and the road in 3-Star road safety rating are equivalent while the length of Good/Very Goor and Poor/Very Poor may be shared between their respective road safety pairs which are 4-Star/5-Star and 1-Star/2-Star. Therefore, **Figure 8.8** is used to provide the proportion of length to be shared within each condition category to generate the required data. The development of the formula related to the data generation is explained in the following sub-chapters.

8.4.1 Generation of Road Condition Data from Type II Data

Based on **Figure 8.8**, the composition of road length in terms of road condition relative to road safety rating may be derived by the following equations:

$$L_{IRI1} = l_{SR1} + 0.5l_{SR2} \quad \textbf{(8.2)}$$

$$L_{IRI2} = 0.5l_{SR2} \quad \textbf{(8.3)}$$

$$L_{IRI3} = l_{SR3} \quad \textbf{(8.4)}$$

$$L_{IRI4} = l_{SR4}/3 \quad \textbf{(8.5)}$$

$$L_{IRI5} = l_{SR5} + 2l_{SR4}/3 \quad \textbf{(8.6)}$$

where:

$L_{IRI1}, L_{IRI2}, L_{IRI3}, L_{IRI4}, L_{IRI5}$ = the composition of road length of each rating

$l_{SR1}, l_{SR2}, l_{SR3}, l_{SR4}, l_{SR5}$ = the relative length of each rating

Table 8.8 Generated network roughness index (IRI)

Survey			Generated		
Star Rating	**Length (km)**	**Percentage**	**Roughness**	**Length (km)**	**Percentage**
★★★★★	1	0.03%	**Very Good**	583	15.79%
★★★★	1163	31.53%	**Good**	582	15.77%
★★★	953	25.84%	**Fair**	953	25.84%
★★	1127	30.56%	**Poor**	376	10.19%
★	444	12.04%	**Very Poor**	1195	32.41%
Total	**3688**	**100%**	**Total**	**3688**	**100%**

From the network Star Rating composition shown in **Table 8.2**, the road condition composition may be generated as shown in **Table 8.8**. The linear relationship between generated roughness and observed road safety ratings is shown in **Table 8.9**.

Table 8.9 Relationship between generated roughness and observed safety ratings

Condition	Network Type					Length	R'^2
	R6	R5	R4	R3	R2		
5-Star	1	0	0	0	0	1	0.9844
V. Good	*458*	*50*	*59*	*17*	*0*	*583*	
4-Star	913	99	118	33	0	1163	1.0000
Good	*457*	*50*	*59*	*17*	*0*	*582*	
3-Star	147	402	300	95	9	953	1.0000
Fair	*147*	*402*	*300*	*95*	*9*	*953*	
2-Star	0	594	340	148	45	1127	1.0000
Poor	*0*	*198*	*113*	*49*	*15*	*376*	
1-Star	5	89	130	165	55	444	0.4151
V. Poor	*5*	*485*	*357*	*264*	*85*	*1195*	

8.4.2 Generation of Road Safety Data from Type III Data

Based on **Figure 8.8**, the composition of road length in terms of road safety rating relatives to road condition may be derived by the following equations:

$$L_{SR1} = l_{IRI1} - l_{IRI2} \quad \textbf{(8.7)}$$

$$L_{SR2} = 2l_{IRI2} \quad \textbf{(8.8)}$$

$$L_{SR3} = l_{IRI3} \quad \textbf{(8.9)}$$

$$L_{SR4} = 3l_{IRI4} \quad \textbf{(8.10)}$$

$$L_{SR5} = l_{IRI5} - 2l_{IRI4}/3 \quad \textbf{(8.11)}$$

where:

$L_{SR1}, L_{SR2}, L_{SR3}, L_{SR4}, L_{SR5}$ = the composition of road length of each rating

$L_{IRI1}, l_{IRI2}, l_{IRI3}, l_{IRI4}, l_{IRI5}$ = the relative length of each rating

Table 8.10 Generated network Star Rating (Vehicle Occupants)

Survey			Generated		
Roughness	**Length (km)**	**Percentage**	**Star Rating**	**Length (km)**	**Percentage**
Very Good	458	12.42%	★★★★★	916	24.83%
Good	916	24.83%	☆☆☆☆	458	12.42%
Fair	1638	44.42%	★★☆	1638	44.42%
Poor	430	11.67%	★★	143	3.89%
Very Poor	246	6.67%	★	533	14.44%
Total	**3688**	**100%**	**Total**	**3688**	**100%**

Table 8.11 Relationship between generated safety ratings and observed roughness

Condition	Network Type					Length	R'^2
	R6	R5	R4	R3	R2		
5-Star	*510*	*199*	*154*	*49*	*5*	*916*	0.9961
V. Good	282	98	71	7	0	458	
4-Star	*228*	*101*	*83*	*42*	*5*	*458*	1.0000
Good	456	201	166	84	9	916	
3-Star	*293*	*635*	*465*	*180*	*65*	*1638*	1.0000
Fair	293	635	465	180	65	1638	
2-Star	*10*	*53*	*37*	*35*	*8*	*143*	1.0000
Poor	30	160	110	105	25	430	
1-Star	*25*	*197*	*149*	*135*	*27*	*533*	0.9899
V. Poor	5	90	76	65	10	246	

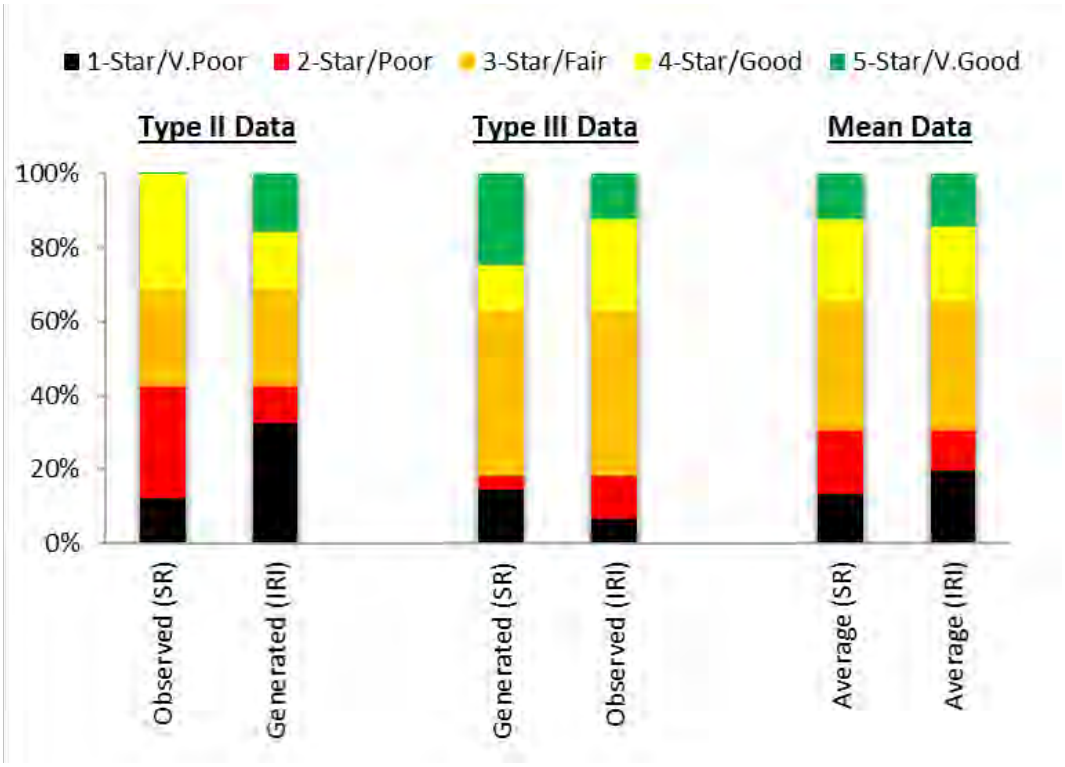


Figure 8.9 Comparison between observed data and generated data

From the network road condition composition shown in **Table 8.2**, the Star Rating composition may be generated as shown in **Table 8.10**. The linear relationship between generated roughness and observed road safety ratings is shown in **Table 8.11**. Comparison summary between observed data and generated data for Type II and Type III data is shown in **Figure 8.9**.

8.5 Conclusion

This chapter presented the validation of the Road Safety Degradation Model from the data that has been gathered for this research. Two groups of data appropriate for application in road management and road safety appraisal have been gathered in terms of roughness and road safety star ratings. A methodology to generate the required data has also been presented which will enable the validation to be carried out. The validated model may also be used to generate data for wider usage of the model.

From the analysis, the model is lack sensitivity to relate Very Poor/Poor condition with 1/2–Star Rating and Good/Very Good condition with 4/5-Star Rating. Therefore, it can be concluded that the model needs further research to accurately identify the road safety degradation curve for Poor road condition vs 2-Star Rating and Good road condition vs 4-Star Rating.

In conclusion, this chapter has presented the inventory data and the preliminary condition assessment to be used in the model integration. These data will be the basis for the forward analysis that will be carried out in the following chapter.

CHAPTER 9

THE IDEAL INTEGRATION MODEL

9.1 Introduction

This chapter is the introduction to the general setup of the proposed model integration. In this chapter, the readiness of the existing models to perform the integration is presented. The main challenge of the existing models is that they exist in two different system environment. However, this challenge is overcome by developing an integration framework that works with the existing models.

In this chapter, all models that have been developed and validated in the previous chapter will be assembled as a complete workable prototype that resembles the envisaged integration of the road safety and road management appraisal model. To carry out the integrated appraisal model, all data that have been collected related to road safety and road management will be analysed by taking all the assumptions and configurations that have been presented earlier into consideration.

The analysis will be carried out on several case studies that represent the appropriate roadworks implementation strategy and budget constraints. The strategy will be performed in three case studies according to the selected prioritisation approach. The designed case studies and the overall evaluation will be used as the sensitivity analysis to demonstrate the application of multiple scenarios of the roadworks implementation strategy. The result of the analysis will be evaluated to further explain the effects of the roadworks implementation strategy in terms of

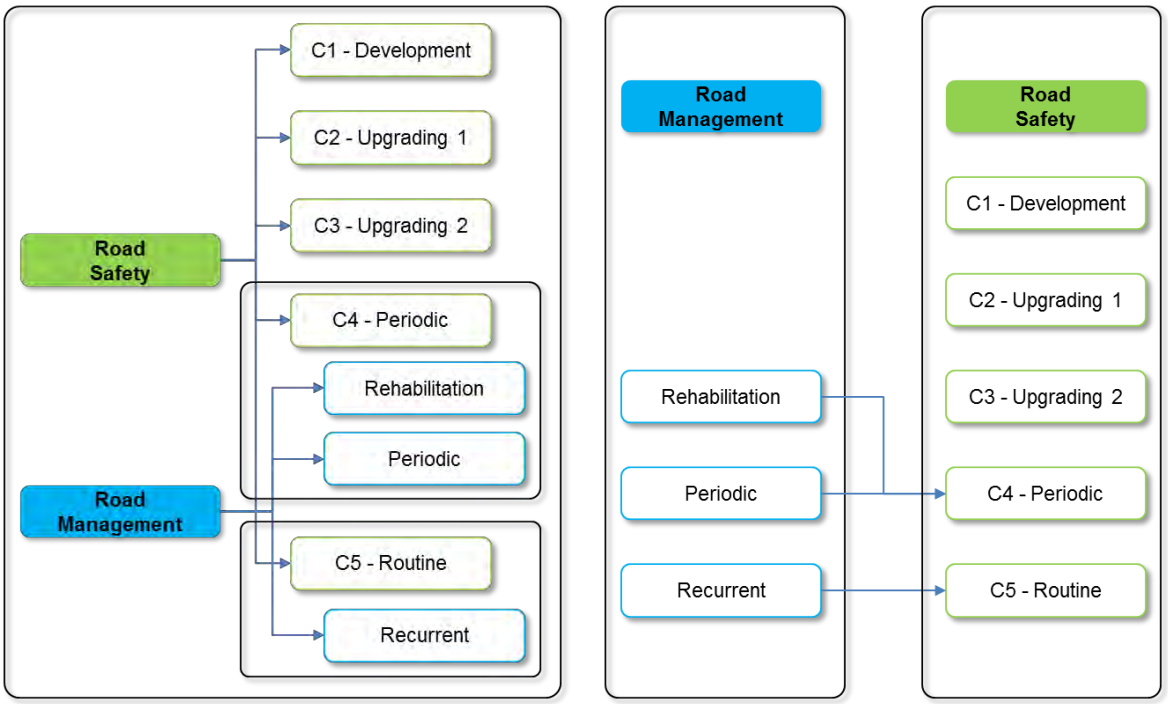
road condition and road safety level. However, the findings of the integration model analysis are presented in **Chapter 10** as a proof-of-concept prototype.

The ideal integration model will also need to consider the rate of the annual road asset deterioration and road safety degradation. This will be presented in the final part of this chapter.

9.2 Integration Method

The main challenge of the existing models is that they exist in two different system environment. Apart from the cost component, the parameters that reflect road management and road safety in both models are not in agreement with each other especially in terms of road condition and intervention level. Currently, there is no available proprietary or established system that may assess both models simultaneously. Besides, there is no established system that may assess the changes in road safety condition. Therefore, the integration method that will be used for the proposed integrated model may need to consider all these deficiencies.

In general, the integration method can be divided into two possible coupling mechanisms namely loose coupling and tight coupling. In *Tight Coupling*, the objects between the integrated systems are dependent on each other, which may reduce the flexibility of the interfacing point. On the other hand, the interfacing objects in *Loose Coupling* are less dependent and may be very flexible for integration (Kaye, 2003; Pautasso and Wilde, 2009). Therefore, the loose coupling may seem very suitable for the integration of road management and road safety models which are not in agreement with each other. In terms of roadworks and road safety countermeasures, the possible integration architecture that explains these coupling methods applicable to this research is shown in **Figure 9.1** with two system boundaries.



a) Tight Coupling **b) Loose Coupling**

Figure 9.1 Possible integration architecture for coupling road management and road safety model

Considering the limitation of the Road Network Evaluation Tools (RONET) and the fitness of the parameters within both road management and road safety models, therefore, it is suggested that the analysis procedure is carried out in a hybrid environment that consists of two operations namely automatic and manual operations. The *Automatic Operation* is the evaluation of the cost components related to the total transport costs including the road administration and road user costs. The evaluation of road condition in terms of roughness that considers road deterioration and road works effects will also be carried out in the automatic operation using RONET. On the other hand, the *Manual Operation* simply consists of the evaluation of road safety level in terms of Star Rating which supposed to consider road safety degradation and countermeasure effects. The manual operation will be carried out in a spreadsheet calculation. The method to integrate road management and road safety model is shown in **Figure 9.2**.

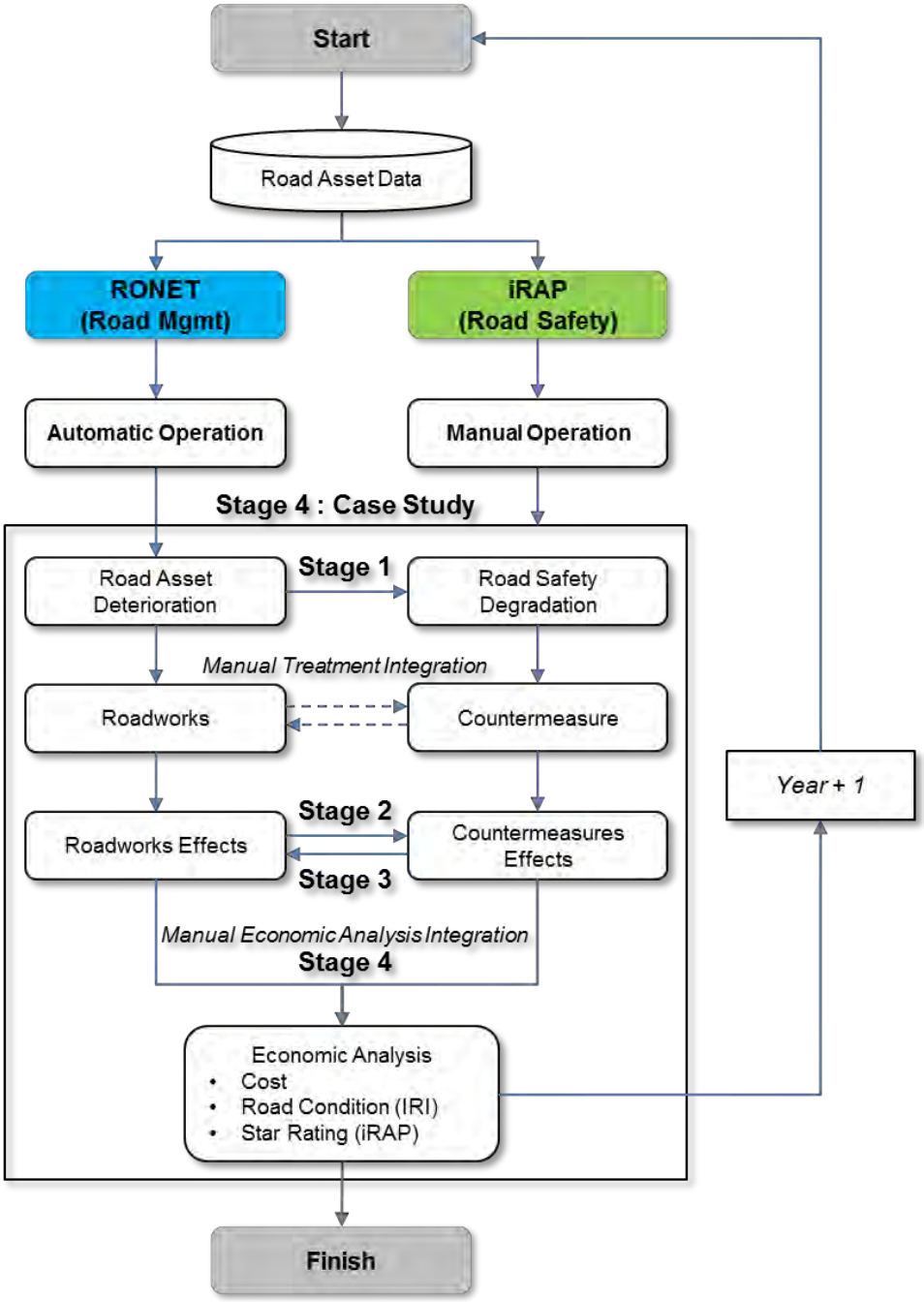


Figure 9.2 Hybrid environment to integrate road management and road safety model

9.3 Prioritisation Approach

The procedure to prioritise the treatment and carry out the related analysis will depend on the treatment selection method and road works implementation strategy. There are several

common treatment selection methods such as defect-based rules, condition index-based rules and more complex rules such as expert systems and optimisation approach. For this research, the strategy to prioritise road works should ultimately aim at choosing the treatments that will tackle both road maintenance and road safety issues.

In a common treatment selection method, for instance, condition-responsive methods and defect-based rules, the selection criteria that are normally used are based on intervention levels. The intervention levels are normally based on certain subjective criteria such as road condition parameters or even time-based fixed schedule (Robinson et al., 1998). This method may not fully optimise the implementation strategy of road maintenance as it may consider only the technical indicators and not the economic indicators (Harvey, 2012). Therefore, as suggested by Robinson et al. (1998), the optimisation approach may be considered in prioritising available treatment options to implement both road maintenance works and road safety countermeasures.

Robinson et al. (1998) have described that the prioritisation methods in road management decision support systems have evolved into the third generation. The evolution simply refers to the level of complexity which can be identified in terms of sectioning, intervention levels, treatment options, basis of economic analysis and method of prioritisation. The *First Generation* prioritisation method can be recognised by the order of priority list which is ranked based on the present condition. The *Second Generation* prioritisation method not only considers the present condition but also the future consequences of the decision to the existing condition. Lastly, the *Third Generation* prioritisation method considers formal optimisation of multiple options and should consider the long-term consequences as a full life-cycle analysis.

According to Robinson et al. (1998), the optimisation approach considers all possible treatment options in each section within the selected road network. From the list of available treatment options, the most appropriate treatment option will be chosen for each section to optimise the

limited budget. The optimum option may be achieved by aiming to fulfil the objective functions which may not be limited to the following:

i. To maximise the asset value over time;
ii. To maximise the quality of road network condition over time;
iii. To minimise the transport costs over time.

For the proposed integrated model, specific objective functions which may be considered as the most suitable to obtain optimum prioritisation are suggested to be specified as the following:

i. Road management:
    a) To maximise the Net Present Value (NPV);
    b) To minimise the total transport cost;
ii. Road safety:
    a) To maximise the road network with a minimum of 3-star road safety level;
    b) To maximise the enhancement of the Star Rating Score (*dSRS*).

To demonstrate the practical concept of the integration and evaluate the implication of the objective functions, a sensitivity analysis will be carried out based on a certain budget scenario. The scenario, which will be presented as case studies, has been designed to concurrently evaluate the road deterioration (RD) and roadworks effects (RWE) as the road condition functions. It will also evaluate road safety degradation (RSD) and countermeasure effects (CE) as road safety functions. The analysis will be carried out over a period of time to emulate a long-term analysis period.

9.4 Case Study Design

As observed by Robinson et al. (1998), many available proprietary decision support systems do not stick to a certain generation of prioritisation. They tend to combine features from various generation suitable to the analysed parameter in their analytical frameworks. For example, a model may consider the first-generation methods to set the intervention level priority, second-generation methods for the performance priority and third-generation methods for the multiple treatment options priority. Therefore, it is suggested that the analysis for this research may also consider combining multiple generations in its prioritisation approach.

To demonstrate the integration model, three case studies were designed and will be presented as shown in **Table 9.1**. The case studies were designed in such a way to carry out the sensitivity analysis on every budget scenario evaluation option that is available in the RONET as shown in **Figure 9.3**. The evaluation of three case studies will be able to provide 19 standards or road work budget scenario with each case study is presented by seven or eight different standards including the Do Minimum and Do Nothing which are equal for each of the case studies. **Table 9.2** shows the standard options applied to each case study.

Table 9.1 Details of designed case studies

Case Study	Implementation Strategy	Evaluation Option
Case I	Benefit-Cost Ratio Strategy	Optimal Standard
Case II	Treatment-Based Strategy	Custom Standard
Case III	Average Budget Strategy	Equal Standard

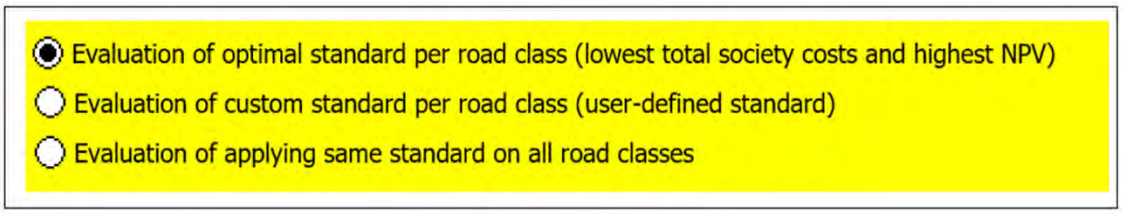


Figure 9.3 Budget scenario evaluation options in the RONET application

Table 9.2 Standard options applied to each case study

Case I	Case II	Case III	Comparison
Optimal +2	Custom +2	Very High Standard	✓
Optimal +1	Custom +1	High Standard	
Optimal	Custom	Medium Standard	✓
Optimal -1	Custom -1	Low Standard	
Optimal -2	Custom -2	Very Low Standard	✓
Optimal -3	Custom -3	-	
Do Minimum	Do Minimum	Do Minimum	✓
Do Nothing	Do Nothing	Do Nothing	

Note: ✓- Standards to be compared

The actual integration strategy of the case studies between the road safety model and road management model may be summarised by **Figure 9.4**. For the discussion in this thesis, only four standards will be examined, which are as follows:

i. the actual standard provided by the budget option itself;

ii. two standards above the actual budget option (+2);

iii. two standards below the actual budget option (-2);

iv. the Do Minimum standard as the base scenario.

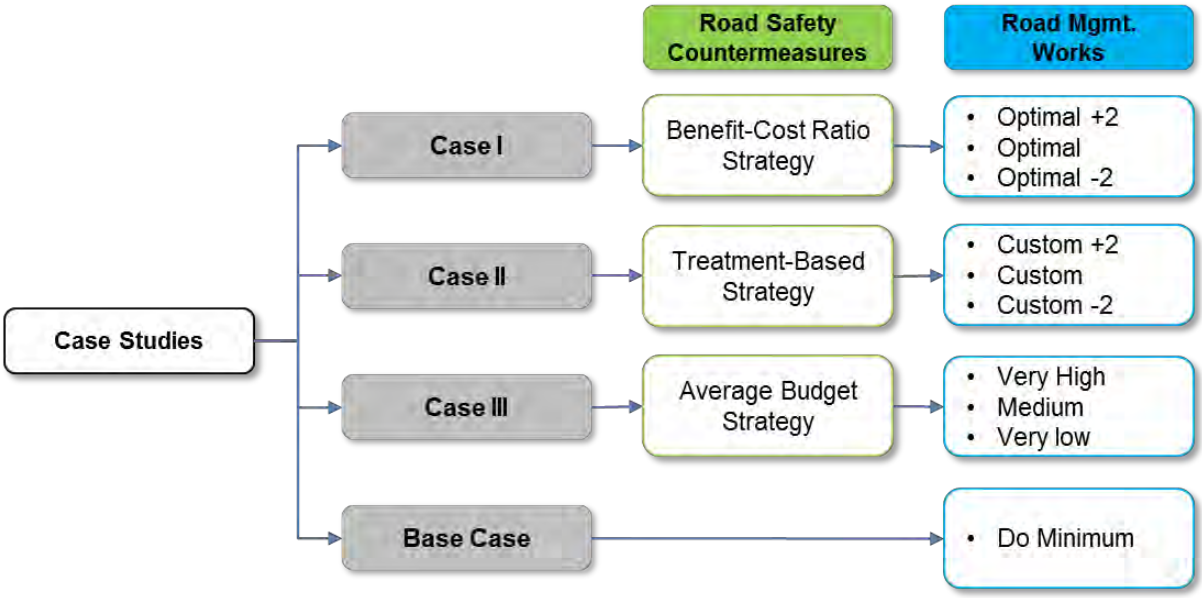


Figure 9.4 Integration strategy of road safety and road management model

9.4.1 Case I: Benefit-Cost Ratio Strategy

Case Study I, namely the *Benefit-Cost Ratio Strategy,* represents a scenario that applies the optimal standard on all the road classes within the network. The optimal standard is the one that produces the lowest present value of total transport costs. The evaluation option that can be chosen to perform this budget scenario in the RONET is 'Evaluation of Optimal Standard per Road Class'.

In this option, the RONET will evaluate the performance of the road network under the different maintenance standards for each road class. Then, it will calculate the annual road agency costs (which consist of rehabilitation works, maintenance works and road safety countermeasures), road user costs and total transport costs over the analysis period. The RONET then calculates the discounted present value of the total transport costs for each standard to determine the optimal standard for each unit of analysis within the selected road

network. In this strategy, Optimal standard options are applied to all roads followed by two standards above the Optimal standard and three standards below the Optimal standard such as Optimal +2, Optimal +1, Optimal -1, Optimal -2, Optimal -3 including Do Minimum and Do Nothing.

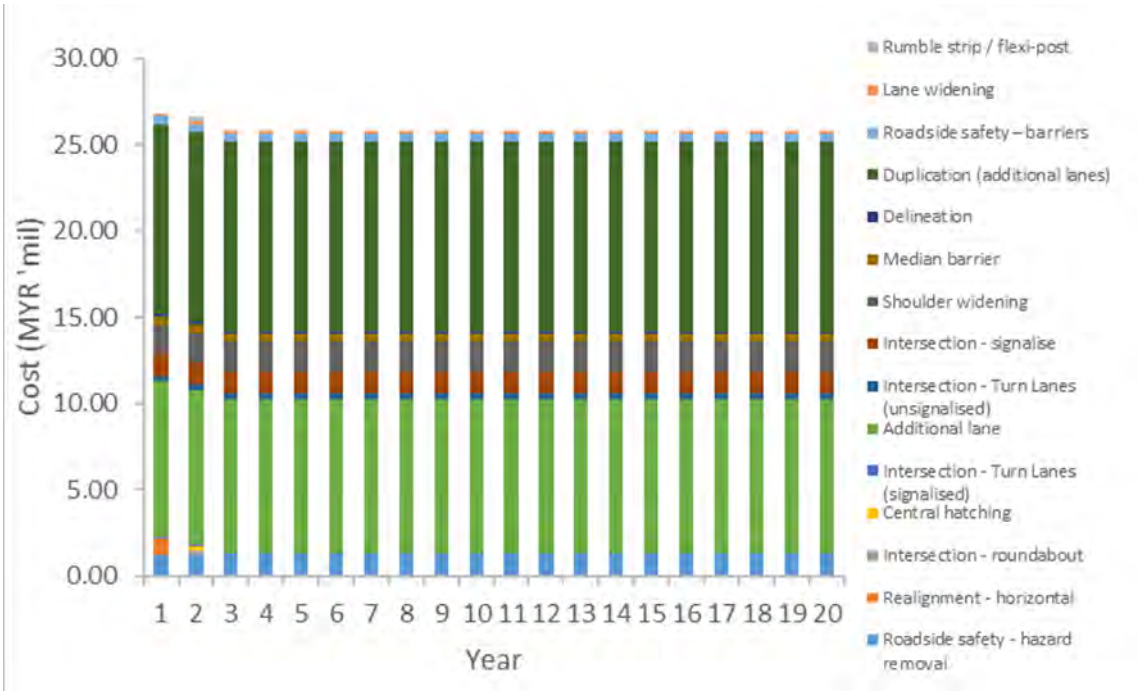


Figure 9.5 Road safety countermeasures annual distribution for Case I

For this case study, the budgeting strategy of road safety countermeasure is prioritised based on the Benefit-Cost Ratio as recommended by the International Road Assessment Programme (iRAP) in the Star Rating Investment Plan (SRIP). The original recommended investment plan is generated from the iRAP's Pilot Project in 2009 as shown in **Appendix 8**. The priority list of the investment plan is shown in **Appendix 9.1** as summarised in **Figure 9.5**.

9.4.2 Case II: Treatment-Based Strategy

The Case Study II, namely the *Treatment-Based Strategy*, is a user-defined budgeting strategy with a specific objective function to maximise the 3-Star and above roads by eliminating the 1-Star and 2-Star roads. The budget scenario that may be chosen to perform this evaluation option in the RONET is 'Evaluation of Custom Standard per Road Class'. In this strategy, the analysis is carried out based on custom standards budget scenario as shown in **Table 9.3**.

The main objective of the Treatment-Based Strategy is to maximise the benefit of a treatment. This can be done by maximising the effects of roadworks to IRI ($dIRI_{RE}$) and the effects of countermeasure to Star Rating ($dSRS_{CE}$) as shown in **Eq. 3.1** and **Eq. 3.2**. To achieve this, the lowest network type, Minor (R2), is applied the Very High Standard while the highest network type, Expressway (R6), is applied the Very Low Standard. Disregard the traffic category of the network, the difference between the higher standard and the lower standard of roads will be reduced.

Table 9.3 Custom standards budget scenario input in RONET

*Network Type	Traffic Category				
	Traffic I	**Traffic II**	**Traffic III**	**Traffic IV**	**Traffic V**
Expressway (R6) ★★★★★	Very Low Standard	Very Low Standard	Very Low Standard	Very Low Standard	Very Low Standard
Highway (R5) ☆☆☆☆	Very Low Standard	Low Standard	Low Standard	Low Standard	Low Standard
Primary (R4) ☆☆☆	Medium Standard	Medium Standard	Medium Standard	Medium Standard	Medium Standard
Secondary (R3) ★★	High Standard	High Standard	High Standard	High Standard	High Standard
Minor (R2) ★	Very High Standard	Very High Standard	Very High Standard	Very High Standard	Very High Standard

* *Network Type is just the homogeneous road section used as the basic unit of analysis and does not prescribe the common traffic level associated with a particular road standard.*

Table 9.4 Treatment-based priority rules

Star Rating	Countermeasure Effects Priority														
★★★★★															
★★★★															
★★★															
★★															
★															
CE Index	C4	C3	C4	C3	C2	C2	C1	C4	C3	C4	C5	C5	C5	C5	C5
Works Type	P2	U3	P1	U4	U1	U2	D1	P3	U5	P4	R5	R4	R3	R2	R1

D: Development U: Upgrading P: Periodic R: Routine/Cyclic

On the other hand, road safety countermeasures are prioritised according to the countermeasure effects with the main objective is to maximise the 3-Star and above roads at the lowest cost as depicted in **Table 9.4**. When there are more than one identified treatments, precedence rules may be applied to set the priority order. The priority of the countermeasure effects is arranged based on the following precedence rules:

i. Countermeasure with 3-Star effects;

ii. Countermeasure that enhances the 1-Star and 2-Star condition;

iii. Countermeasure that enhances the 3-Star condition;

iv. Countermeasure that enhances the 4-Star condition;

v. Countermeasure with lower cost;

vi. Routine works (C5) are carried out where and when required which are prioritised by network type.

Table 9.5 Treatment-based priority matrix

Works Category	Works Type	Countermeasure Effects	Traffic Category		
			V	IV	III
Periodic	**P2**	**C4**	*1*	*2*	*3*
Upgrading	**U3**	**C3**	*4*	*5*	*6*
Periodic	**P1**	**C4**	*7*	*8*	*9*
Upgrading	**U4**	**C3**	*10*	*11*	*12*
Upgrading	**U1**	**C2**	*13*	*14*	*15*
Upgrading	**U2**	**C2**	*16*	*17*	*18*
Development	**D1**	**C1**	*19*	*20*	*21*
Periodic	**P3**	**C4**	*22*	*26*	*30*
Upgrading	**U5**	**C3**	*23*	*27*	*31*
Periodic	**P4**	**C4**	*24*	*28*	*32*
Routine / Cyclic	**R1 – R5**	**C5**	*25*	*29*	*33*

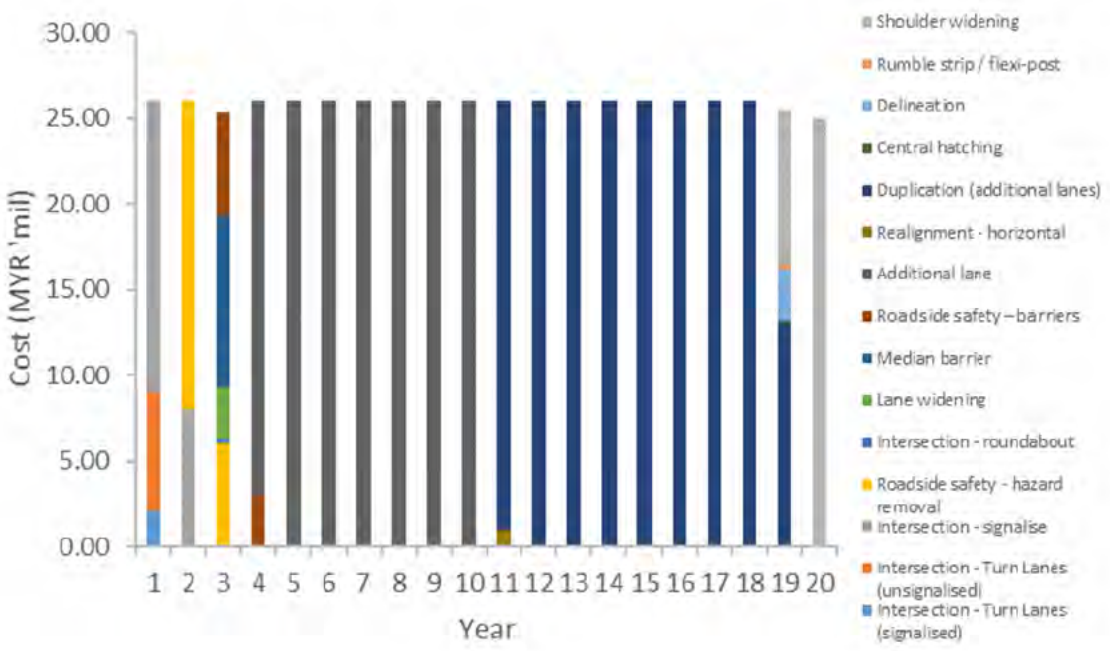


Figure 9.6 Road safety countermeasures annual distribution for Case II

By considering the traffic category appropriate for this research, the above countermeasure effects priority may be restructured by the treatment-based priority matrix as shown in **Table 9.5**. From this matrix, a higher priority has been given to the type of work over the traffic category to the first seven countermeasures. This is imposed to maximise the number of road users benefited with the minimum 3-Star roads. For the following countermeasures, priority is given to the road with traffic category V over the other two traffic categories. The prioritised list for this case study is also shown in **Appendix 9.2** as summarised in **Figure 9.6**

9.4.3 Case III: Average Budget Strategy

Case Study III, namely the *Average Budget Strategy*, may be considered as a control measure for this research. The budget scenario that can be chosen to perform this evaluation option in the RONET is 'Evaluation of Applying the Same Standard on all Road Classes'. In this strategy, all seven standard options are applied to all roads such as Very High Standard, High Standard, Medium Standard, Low Standard, Very Low Standard, Do Minimum and Do Nothing for the pavement maintenance works.

In this case study, the road safety countermeasures are prioritised as recommended by the International Road Assessment Programme (iRAP) in the Star Rating Investment Plan (SRIP) which has been provided for the iRAP pilot project. The recommendations are spread out within 20-years budget analysis to average out the cost of the countermeasures annually. The original recommended investment plan is shown in **Appendix 8**. The prioritised list which has been spread out within 20-years budget analysis is shown in **Appendix 9.3** as summarised in **Figure 9.7**.

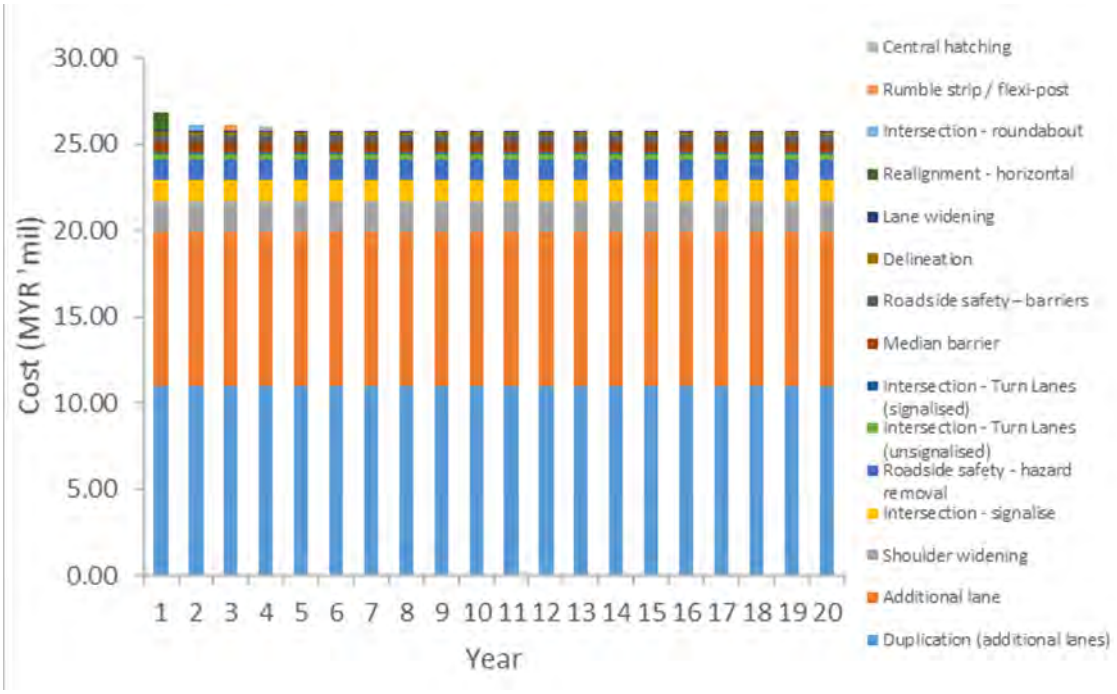


Figure 9.7 Road safety countermeasures annual distribution for Case III

9.5 Road Asset Deterioration and Road Safety Degradation Assessment

In this research, the assessment of road asset deterioration is automatically carried out using the Road Network Evaluation Tools (RONET) as shown in **Figure 9.2**. As the road safety degradation model is far from its maturity state, the proposed model of road safety degradation as introduced in **Chapter 5** and the relative imputation method as introduced in **Chapter 8** will be applied in this research. Therefore, **Figure 5.3** and **Figure 8.8** are referred to assess road safety degradation relative to physical road deterioration.

It has also been presented in **Chapter 5** that road safety degradation is directly influenced by skid resistance and road condition. In this instance, the road condition is highly contributed by the overall roughness of the road network. As Markov chains have been used in numerous

pavement management systems to model the performance of pavements, it has been suggested that a similar probability chain is used to establish the road safety degradation model.

A Markov chain is a stochastic model that describes a sequence of possible events in which the probability of each event is subject to the condition of the previous event (Butt et al., 2004). Based on Markov chain probability, some part of the pavement will deteriorate while the rest will still in a good condition. The chain will continue in the following period when some other part of the good pavement will deteriorate while the rest will still in a good condition as shown in **Figure 9.8**. Therefore, the distribution of the road safety condition state needs to be explored to develop the road safety degradation model.

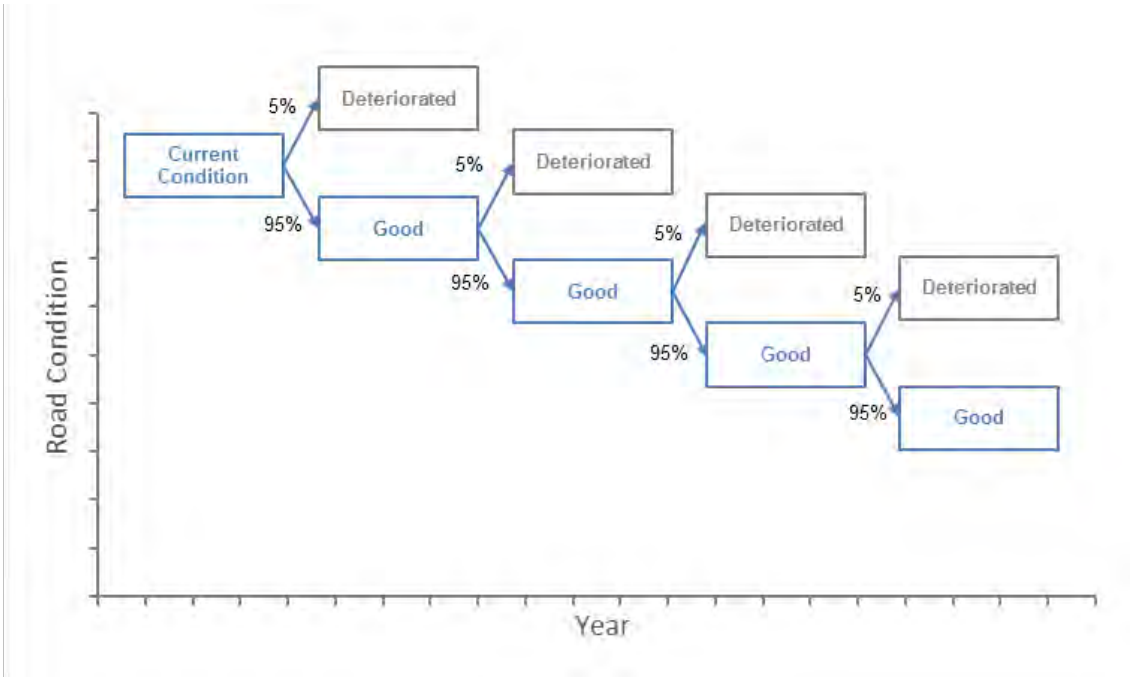


Figure 9.8 Markov chain probability in pavement deterioration

For the sensitivity analysis, the effects of road deterioration on road safety degradation may be analysed in certain conditions. For this purpose, it may be assumed that the probability of deterioration rate for a newly laid pavement is 5% annually which cumulatively will reach deterioration of 100% in a 20-year period of analysis. Therefore, the distribution of annual and

cumulative deterioration may be depicted with the chart shown in **Figure 9.9**. **Figure 9.10** shows the condition of an asset with a constant 5% deterioration rate based on Markov chain probability model.

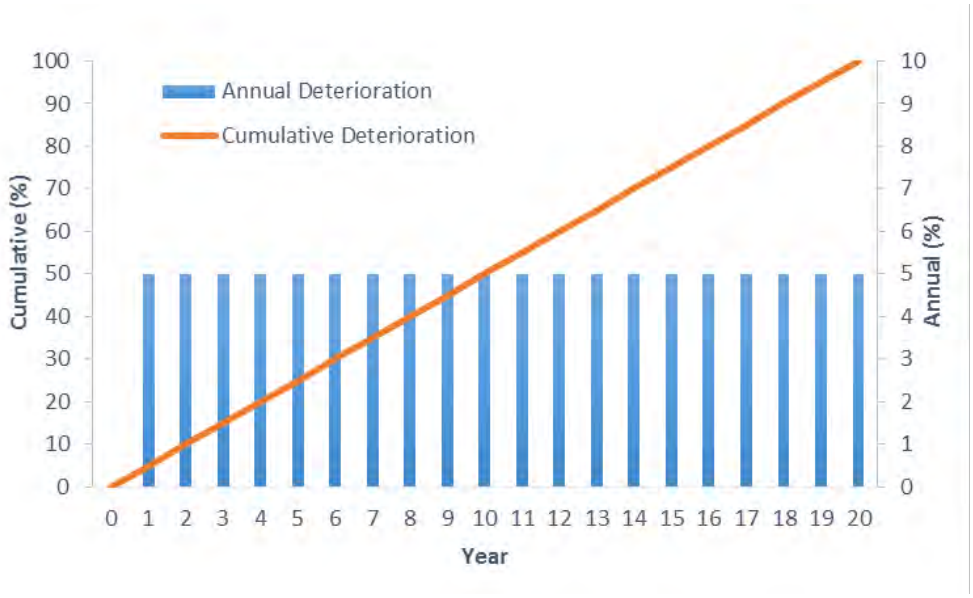


Figure 9.9 Distribution of deterioration with a constant 5% deterioration rate

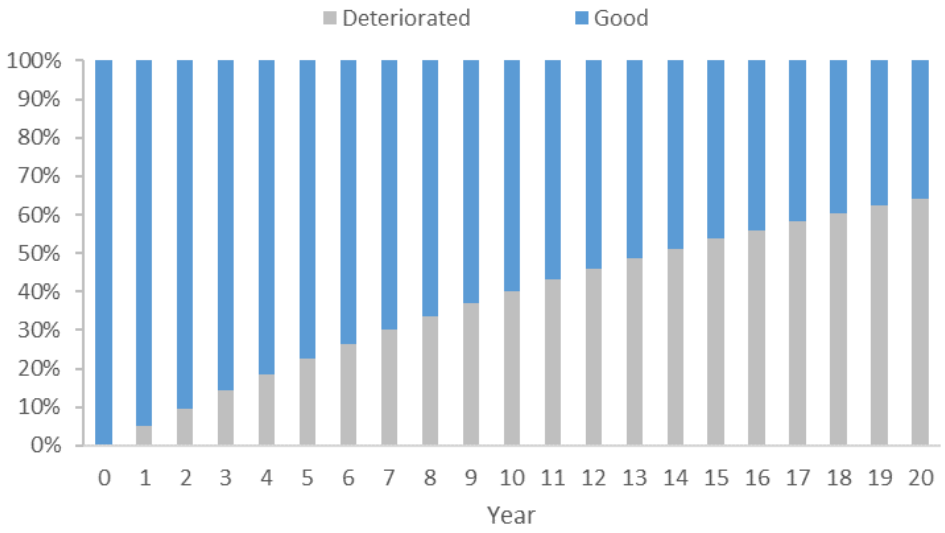


Figure 9.10 Condition of an asset with a constant 5% deterioration rate

The deterioration of road as observed in **Figure 9.10** is a perfect result of Markov chain transition as it involves only two conditions, for instance, the deterioration constantly increased from a totally good condition road. However, a unique pattern will be shown when it involves more condition levels. Assuming the proportion of each condition level at the initial stage of the analysis is equal, the deterioration transition of the road involving two, three, four or five condition levels may be shown by **Figure 9.11**.

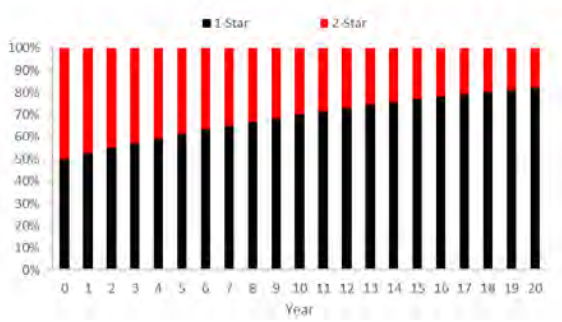


Figure 9.11(a) Two condition levels

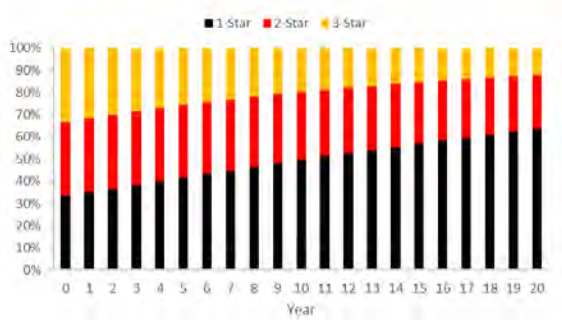


Figure 9.11(b) Three condition levels

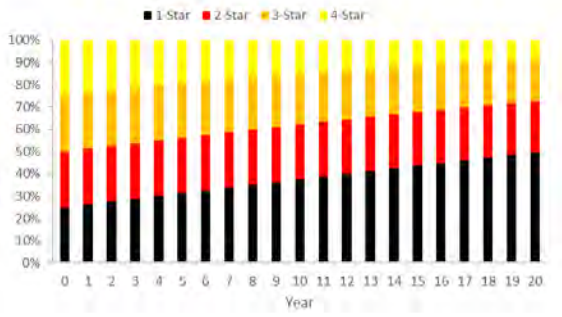


Figure 9.11(c) Four condition levels

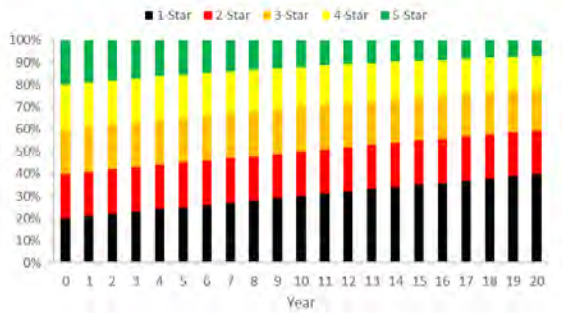


Figure 9.11(d) Five condition levels

Figure 9.11 Multiple condition levels of an asset with a constant 5% deterioration rate

From **Figure 9.11**, even though the physical road deterioration is set at a constant 5% rate, it is shown that the total road deterioration rate experienced by multiple condition levels is multiplied by *n*-1 numbers of condition levels. For example, the yearly total road deterioration rate experienced by five condition levels is [(5-1)*5%] or equivalent to 20% annually.

Therefore, for this research, the yearly total road safety degradation rate is assumed to be 20% annually based on five levels of the International Road Assessment Programme (iRAP) road safety Star Rating.

Based on the relationship of road safety rating and road roughness, it is learnt that the relative road safety degradation (RSD) rate between each road safety level against the road deterioration rate varies. Therefore, the road safety degradation (RSD) rate relative to the actual road deterioration rate for each road safety level change has to be derived from the road safety rating and road roughness relationship as shown in **Figure 8.8**. The adjusted annual road safety degradation (RSD) rate for each road safety level change as derived from this relationship is summarised in **Table 9.6**.

Table 9.6 Adjusted annual road safety degradation (RSD) rate

Road Safety Degradation	Adjustment Rate (%)
5 ➔ 4	2.0
4 ➔ 3	4.0
3 ➔ 2	12.0
2 ➔ 1	2.0
***Total**	**20.0%**

*Total deterioration rate for *n* condition levels = (*n*-1)*5%

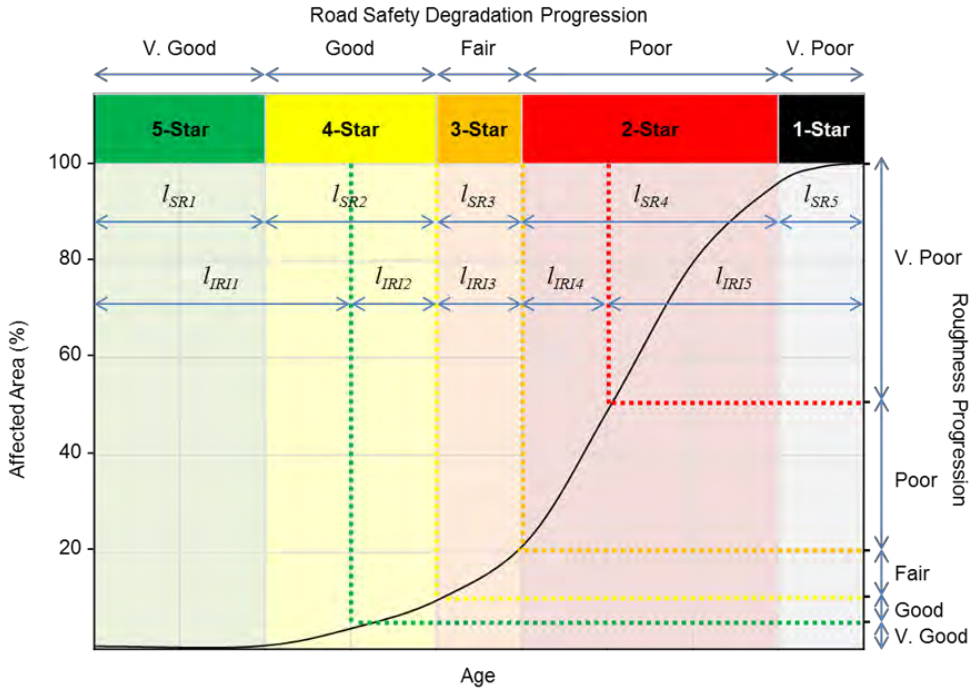


Figure 8.8 Relationship of road safety rating (iRAP) and road roughness (IRI)

In reality, the distribution of annual road deterioration rate within a period of the analysis also varies. In general, it may be assumed that the annual road deterioration rate experienced by existing road is constant at a certain rate as shown in **Figure 9.12(a)** on the left graph. The transition of road safety degradation (RSD) for this distribution is shown by the graph on the right.

Considering the adjusted road safety degradation (RSD) rate as shown in **Table 9.6** and using the same distribution of annual road deterioration rate, the transition of road safety degradation (RSD) will result in a slightly different pattern as shown in the graph on the right of **Figure 9.12(b)**. It is shown that the 2-Star roads increased rapidly compared to the other road safety levels as the degradation from 3-Star roads to 2-Star roads are at a 12% rate.

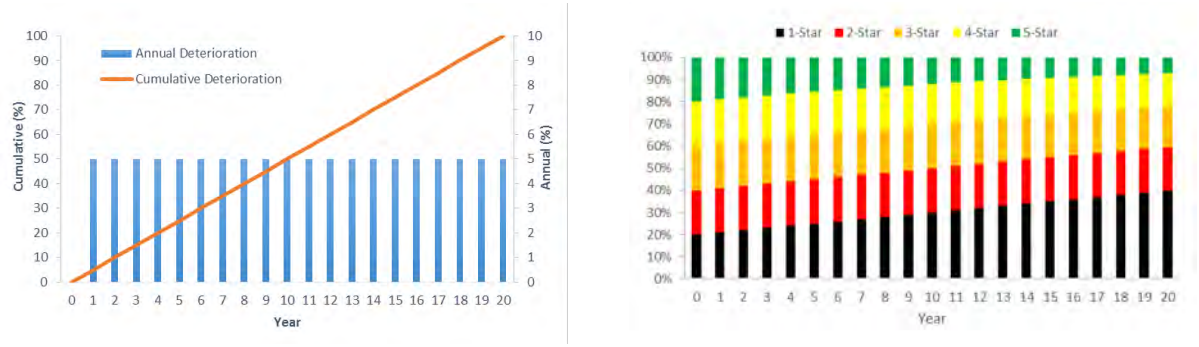


Figure 9.12(a) Deterioration of existing road at a constant 5% rate

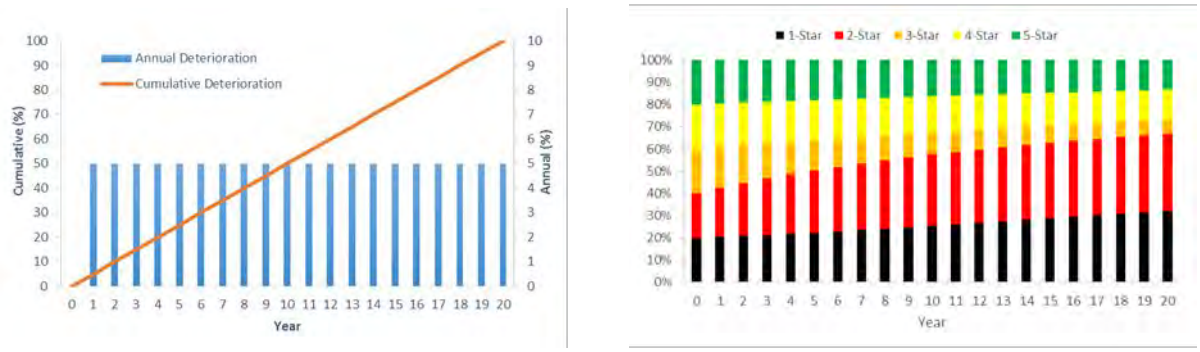


Figure 9.12(b) Deterioration of existing road at a constant 5% rate with road safety degradation adjustment

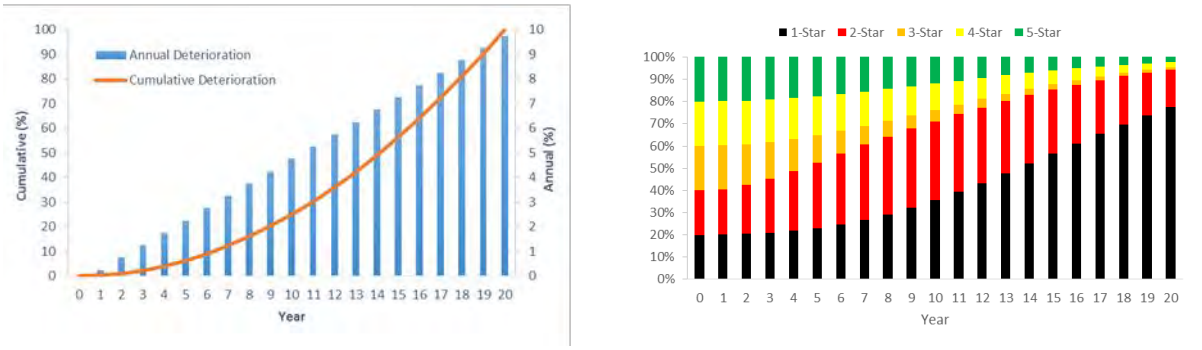


Figure 9.12(c) Deterioration of new road with road safety degradation adjustment

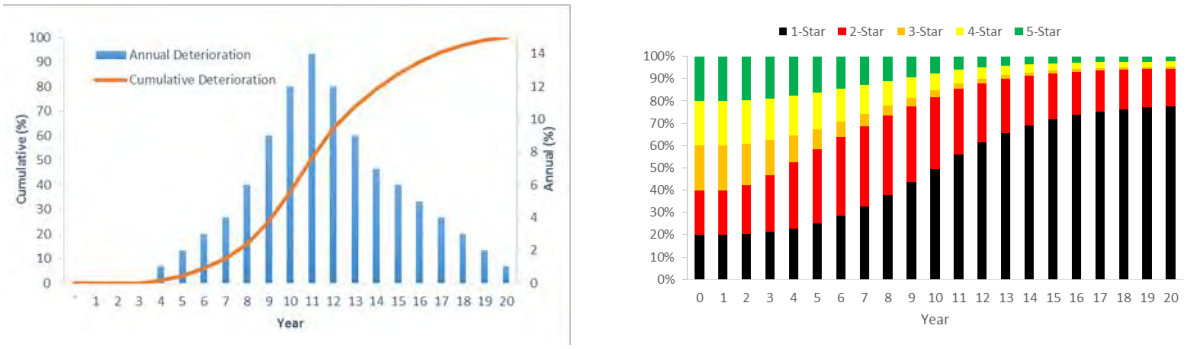


Figure 9.12(d) Deterioration of normal distribution with road safety degradation adjustment

Figure 9.12 Condition of an asset with respective deterioration distribution and road safety degradation adjustment

Similarly, **Figure 9.12(c)** and **Figure 9.12(d)** respectively represent the pattern that may be experienced by a new road and a more realistic random road in which the annual deterioration is normally distributed throughout the analysis period. In a general concept, a new road may experience an increment in the amount of annual road deterioration throughout the analysis period. In reality, a random road section may experience a normally distributed deterioration that cumulatively follows a sigmoidal curve. Even though the sigmoidal curve resembles most of the road deterioration models, it represents the behaviour of a road section within the same age and not the overall road network that may consist of various ages of pavement.

However, with the magnitude of the deterioration and degradation is not yet established within the model, it is suggested that a constant rate of 5% deterioration with road safety degradation adjustment as shown in **Figure 9.12(b)** is the best option for this research. It fulfils the condition of the study area which mostly consists of the existing road network. Even though the 5% constant rate deterioration may not fit the actual pavement deterioration behaviour based on the Markov chain probability, it is assumed that this deterioration distribution may provide a better representation of the deterioration behaviour for the existing road network.

The effect of road safety degradation (RSD) will be included in the integrated assessment of road asset and road safety investment appraisal. **Figure 9.13** shows the road safety degradation (RSD) for the study area which has been derived from the proposed Road Safety Degradation (RSD) model. It shows that the average Star Rating gradually dropped from 2.8 to 2.1. The configuration dataset is available in **Appendix 10**.

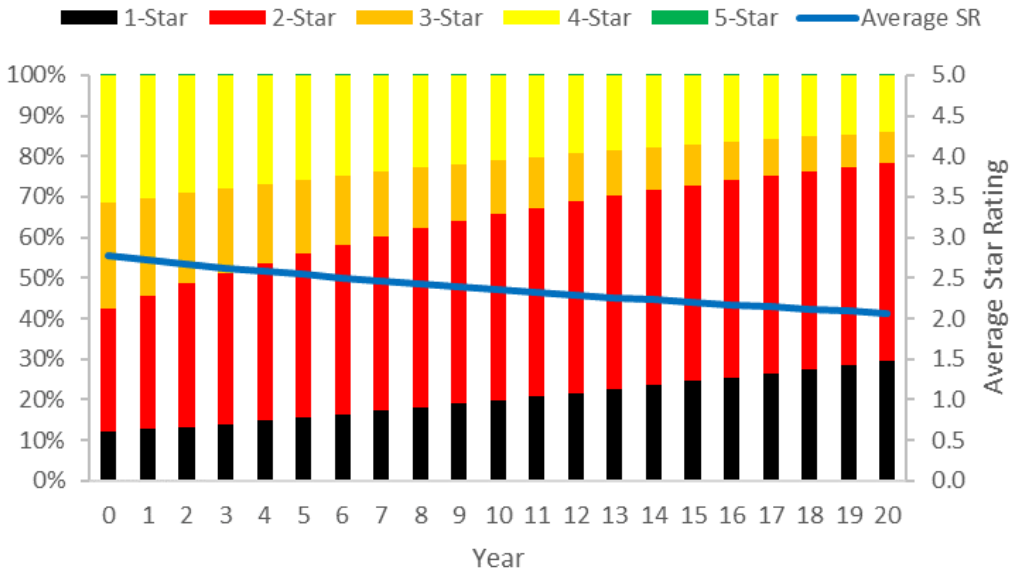


Figure 9.13 Road safety degradation for the study area

The Average Star Rating (ASR) is calculated using the following **Eq. 9.1**:

Average Star Rating (ASR),

$$= \frac{(aL_{SR1})+(bL_{SR2})+(cL_{SR3})+(dL_{SR4})+(eL_{SR5})}{L} \quad \textbf{(9.1)}$$

$$= \frac{(1\times L_{SR1})+(2\times L_{SR2})+(3\times L_{SR3})+(4\times L_{SR4})+(5\times L_{SR5})}{L} \quad \textbf{(9.2)}$$

where:

a, b, c, d, e	=	a constant equivalent to the respective Star Rating
$L_{SR1}, L_{SR2}, L_{SR3}, L_{SR4}, L_{SR5}$	=	the composition of road length for each rating
L	=	total road length

9.6 Conclusion

This is the introduction to the general setup of the ideal proposed model integration. In this chapter, the readiness of the existing models to perform the integration is presented. The main challenge of the existing models is that they exist in two different system environment. However, this challenge is overcome by developing an integration framework that works with the existing models. The findings of the integration model analysis are presented in **Chapter 10** as a proof-of-concept prototype.

The ideal integration model has been presented in this chapter. The integration framework adopted a loose coupling method to integrate the road asset management assessment and road safety assessment as shown in Figure 9.2. The road asset management assessment will be carried out in automatic operation using the RONET and the road safety assessment will be carried out using the manual operation approach. The ideal integration model will also consider the rate of the annual road asset deterioration and road safety degradation.

CHAPTER 10

PROOF-OF-CONCEPT PROTOTYPE FOR INTEGRATED MODEL

10.1 Introduction

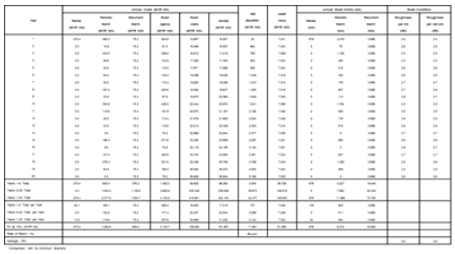
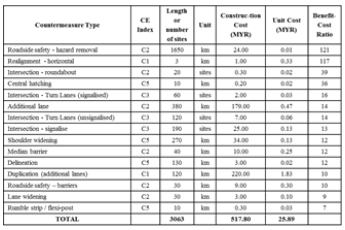
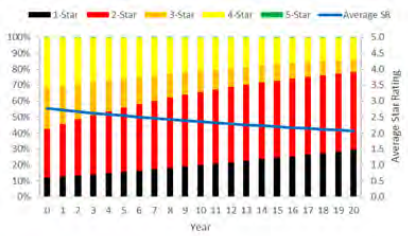
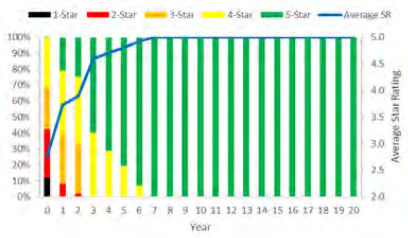
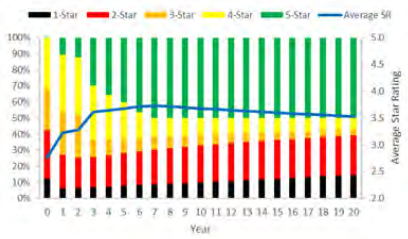
The validation of the integration framework is analysed based on the result of life-cycle analysis from the three case studies. Although the case studies were design based on the capabilities and limitation of the Road Network Evaluation Tools (RONET), they may cover most of the possible implementation strategies applicable to both road management and road safety programme. Therefore, this subchapter will review the outcome of all case studies in terms of cost, road condition and road safety level.

The details of the analysis are presented in **Appendix 9**, **Appendix 10** and **Appendix 11** of this thesis as indexed in **Table 10.1**. **Appendix 9** consists of road safety and road management work programme as well as the result of the Road Network Evaluation Tools (RONET) analysis. The result which covers all three cases represents the road management assessment. Road condition and road agency costs are the most important output parameters to be assessed from this assessment as they are the key technical evaluation and economic analysis used in most decision-support tools.

Appendix 10 is the detailed result of Road Safety Degradation (RSD) which represents the evaluation of the life-cycle road safety rating reduction due to deterioration (*dRSR*) of the road assets. The overall road safety assessment for all cases based on their respective design of case studies is presented in **Appendix 11**. The main output parameter for this assessment is the

average road safety Star Rating. The output is presented in three steps which indicate the epitome of all the three parameters as derived from **Eq. 3.2**.

Table 10.1 Index for the details of result and analysis

	Road Management Assessment and Work Programme • **Appendix 9.1.4** Optimal Standard • **Appendix 9.2.4** Custom Standard • **Appendix 9.3.4** Equal Standard
	Road Safety Countermeasures Priority • **Appendix 9.1.2** Optimal Standard • **Appendix 9.2.2** Custom Standard • **Appendix 9.3.2** Equal Standard
	Road Safety Degradation, *dRSR* (RSD) • **Appendix 10**
	Annual Countermeasure Effects Deviation ($dRSR_{CE}$) • **Appendix 11.1.1.2** Optimal Standard • **Appendix 11.2.1.2** Custom Standard • **Appendix 11.3.1.2** Equal Standard
	Annual Road Safety Rating (RSR_{n+1}) • **Appendix 11.1.1.3** Optimal Standard • **Appendix 11.2.1.3** Custom Standard • **Appendix 11.3.1.3** Equal Standard

10.2 Do Minimum as the Base Scenario

As a quick recap, the Do Minimum is a budget standard where the only capital road work applied over the evaluation period is reconstruction when the roughness has reached a very high point. Meanwhile, the Do Nothing is a budget standard where no capital road works are applied over the evaluation period. In other words, the recurrent works or routine maintenance works are the main roadworks that contribute to the average condition of the network. In many scenarios, the Do Minimum and Do Nothing standard may produce almost identical outcome by the Road Network Evaluation Tools (RONET).

However, for this research, the Do Minimum standard has been chosen as the base scenario for the economic analysis comparison. As a minimum requirement of road management, this standard has been designed to only consider the road management aspect of roadworks. Therefore, road safety countermeasures have entirely been ignored to be part of the work programme. Rather than the Do Nothing, the outcome from the Do Minimum standard has come out with a significantly minimum road maintenance regime that may excitingly enlighten us on this subject.

In this case, the RONET analysis has come out with a road maintenance regime as shown in **Appendix 9**. **Figure 10.1** and **Figure 10.2** respectively shows the effect of Do Minimum standard on road network roughness and road safety level. For all three cases, the same pattern of Do Minimum standard has been expected as they are analysed using the same initial data and model configurations.

In terms of road agency cost, recurrent maintenance works are implemented throughout the analysis at the cost of RM18.8 million per year. However, about five times rehabilitation works have been suggested in Year-4, Year-12, Year-13, Year-14 and Year-18. The most significant

works have been implemented in Year-4 and Year-12/13 at the cost of RM98.4 million, RM44.0 million and RM116.0 million respectively hence the pattern of the graph increased rapidly during these periods.

The average roughness for each standard is provided from the RONET Performance Assessment Model (PAM) analysis in the Annual Work Programme as attached in **Appendix 9**. Conversely, the average Star Rating for each standard is generated from the Road Safety Model (RSM) analysis based on the Road Safety Degradation as attached in **Appendix 10** and the Countermeasure Effects as attached in **Appendix 11**.

In terms of the average roughness of the network, it has increased from 5 m/km at the beginning of the analysis to 9 m/km at the end of the analysis. A slight reduction of roughness has been recorded on Year-4 and Year-12/13 when major capital work has been carried out. Based on the target average roughness, it is shown that the Do Minimum strategy does not meet the objective to maintain a maximum average roughness of 4.5 m/km.

For road safety, the selected network has recorded a declining average Star Rating from 2.8 at the beginning of the analysis to 2.5 at the end of the analysis. A slight increase of roughness has been recorded on Year-4 and Year-12/13 when major capital work has been carried out. Based on the target average Star Rating, it is shown that the Do Minimum strategy does not meet the objective to maintain a minimum average Star Rating of 3-star.

From **Figure 10.1** and **Figure 10.2**, it can be concluded that the Do Minimum strategy may not be adequate to preserve the road condition and the road safety rating of the network to achieve the required target objectives. More importantly, this is a piece of evidence that there is consistency between roughness and road safety level in terms of their degradation and their effects on road works. It is a valid strong point that can be observed in the following figures that concern all other implementation strategies.

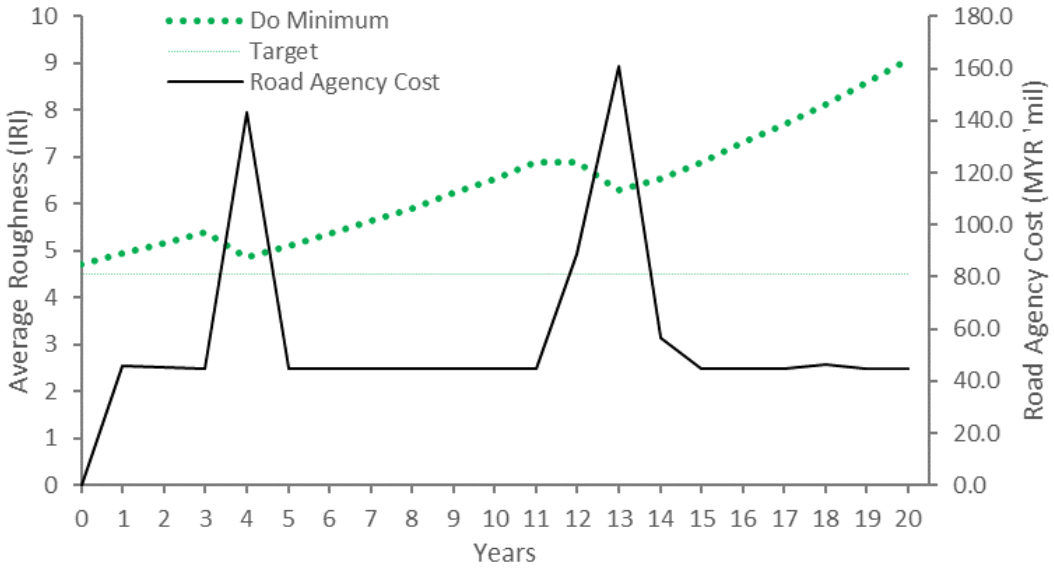


Figure 10.1 Effect of Do Minimum Strategy on road network roughness

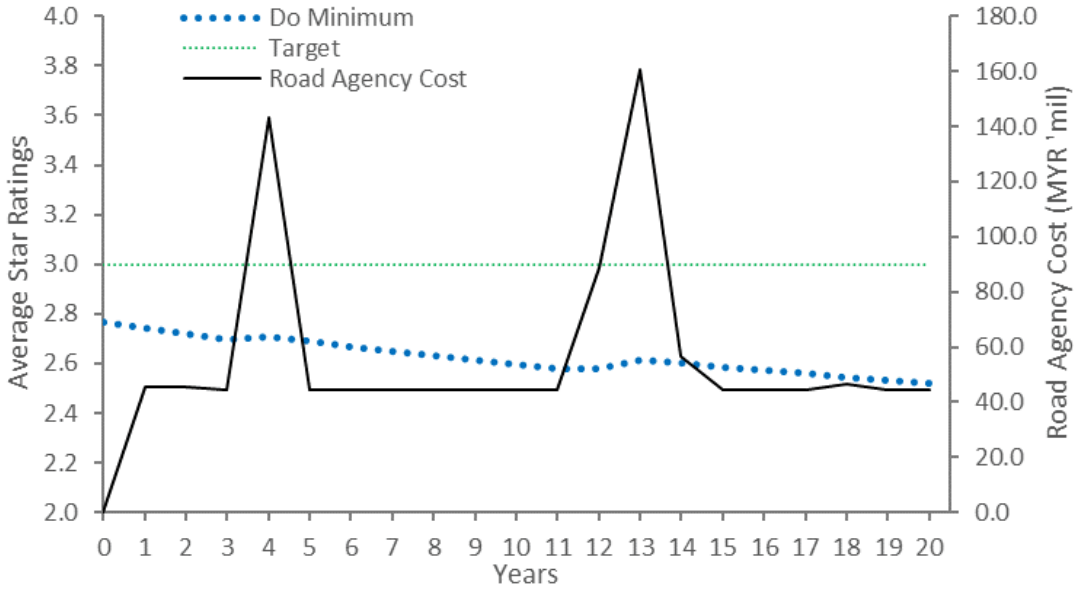


Figure 10.2 Effect of Do Minimum Strategy on road network safety

10.3 Impact of Benefit-Cost Ratio Strategy (Case I)

Figure 10.3 shows the distribution of road agency cost based on the Benefit-Cost Ratio Strategy (Case I) and **Table 10.2** shows the cost comparison for each standard. A historical average of RM180.0 million has been included in **Figure 10.3** as an indicative measure based on the average previous 5-years maintenance programme. From **Figure 10.3**, it is shown that Optimal +2 and Optimal Standard have almost identical work programme with the Optimal +2 opted to a higher cost magnitude.

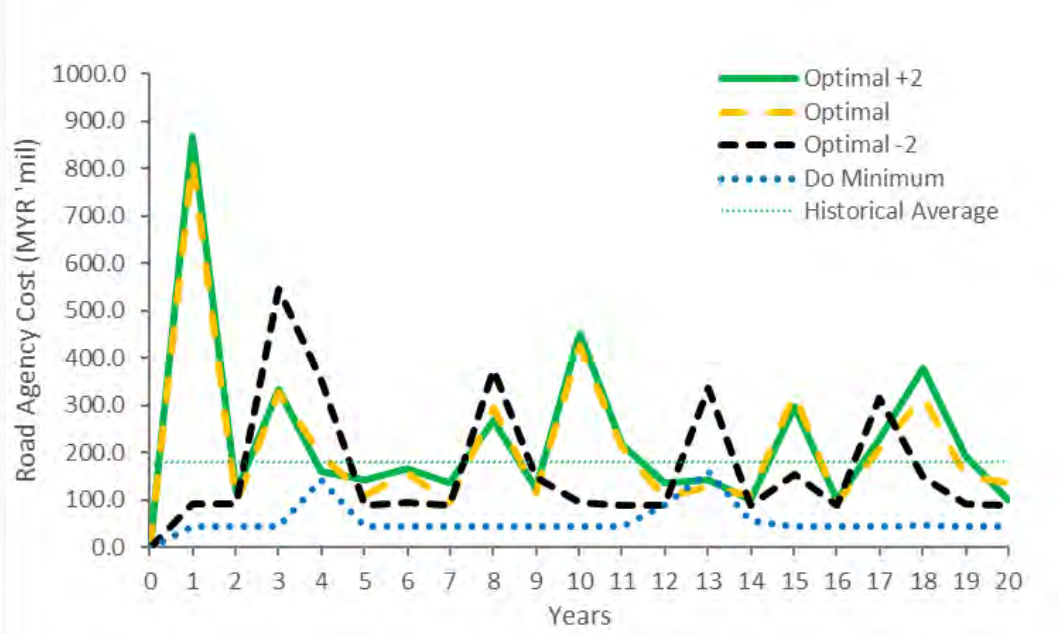


Figure 10.3 Distribution of road agency cost based on the Benefit-Cost Ratio Strategy

In general, the work programme suggested that three cycles of major periodic maintenance work be carried out throughout the analysis period. It has introduced rehabilitation works in the early stage of the analysis and the other two major periodic maintenance works at the middle and towards the end of the analysis. In between the three major periodic maintenance works,

two more additional minor periodic maintenance works are included in the work programme making it up to about five cycles of periodic maintenance works. This makes the periodic maintenance works to be carried out at least every year or alternate years.

Table 10.2 Road agency cost comparison based on the Benefit-Cost Ratio Strategy

Budget Scenario	Total Cost (MYR 'mil)	Yearly Average (MYR 'mil)	*Cost Difference
Optimal +2	4670.7	233.5	29.7%
Optimal	4427.1	221.4	23.0%
Optimal -2	3480.3	174.0	-3.3%
Do Minimum	1166.4	58.3	-67.6%
*Historical Average	3600.0	180.0	0.0%

In terms of average roughness and safety level, the Optimal +2 and Optimal Standard recorded a significant increase in quality for both aspects. The average roughness has reduced rapidly from 4.7 m/km to 2.6 m/km since the first year of the rehabilitation works and maintain throughout the 20-years of analysis as shown in **Figure 10.4**. The average Star Rating accounted for the Optimal +2 and Optimal Standard has increased in several years contributed by several types of roadworks and road safety countermeasures as shown in **Figure 10.5**. It has climbed up from 2.8 to 3.2 in Year-1, to 3.7 in Year-5 and slowly decreased due to the effects of road safety degradation towards the end of the analysis.

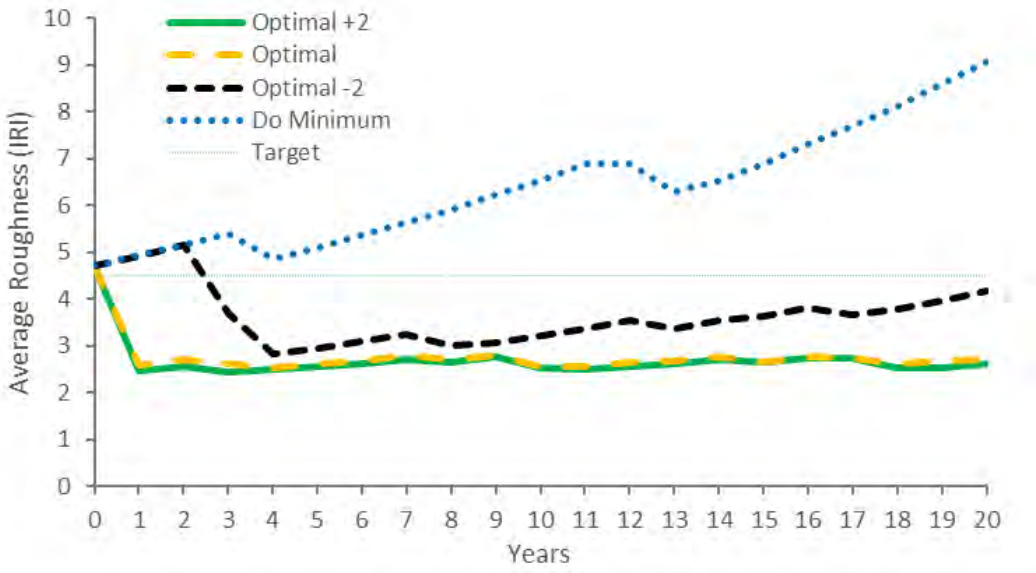


Figure 10.4 Effect of Benefit-Cost Ratio Strategy on road network roughness

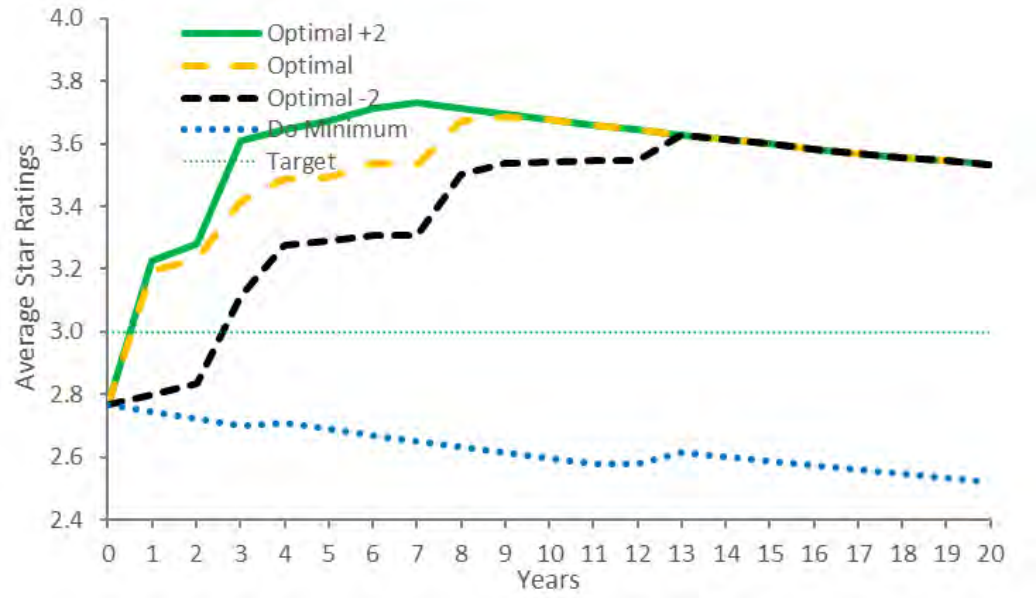


Figure 10.5 Effect of Benefit-Cost Ratio Strategy on road network safety

For the Optimal -2 standard, about four cycles of delayed periodic maintenance works have been introduced with a lower cost magnitude compared to the other two higher standards. The average roughness has increased from 4.7 m/km to 5.2 m/km as an effect of the delayed

periodic maintenance works. However, the average roughness has reduced rapidly to 2.8 m/km in Year-4 due to subsequent rehabilitation and periodic maintenance works that have been carried out in two consecutive years. The average roughness for this standard suffers slight road condition deterioration from time to time due to the minimum magnitude of road maintenance. However, this effect has been kept at a minimum by the following three cycles of periodic maintenance works as shown in **Figure 10.4**.

The average Star Rating accounted for the Optimal -2 has increased in several years contributed by several types of roadworks and road safety countermeasures as shown in **Figure 10.5**. Clearly, it has climbed up from 2.8 to 3.6 in four cycles affected by the respective works in Year-3/4, Year-8 and Year-13. The average Star Rating slowly decreased after Year-13 due to the effects of road safety degradation towards the end of the analysis.

In terms of cost, the yearly average cost of Optimal +2 and Optimal standards is MYR233.5 million and MYR221.4 respectively, far exceeding the historical average of MYR180.0 million between 22.7% to 29.4%. However, the yearly average cost of Optimal -2 standards is MYR174.0 million and within the historical average.

As an overall performance, all of the implementation standards in the Benefit-Cost Ratio Strategy have achieved the minimum target of average road condition and average Star Rating as recognised in the International Roughness Index (IRI) and International Road Assessment Programme (iRAP). Suitable with the selection of the analysis option, it is shown that this strategy has been implemented to minimise the total transport cost and maximise the net present value (NPV) by increasing the road quality at the beginning of the analysis and maintaining the quality throughout the analysis period.

10.4 Impact of Treatment-Based Strategy (Case II)

Figure 10.6 shows the distribution of road agency cost based on the Treatment-Based Strategy (Case II) and **Table 10.3** shows the cost comparison for each standard. From **Figure 10.6**, it is shown that Custom +2 Standard has opted a high-cost rehabilitation works at the start of the analysis followed by various periodic maintenance throughout the analysis. The Custom Standard have included a couple of lower-cost rehabilitation works at the start of the analysis followed by various periodic maintenance throughout the analysis. On the other hand, the Custom -2 Standard implemented a very low maintenance budget with four cycles of rehabilitation works throughout the analysis.

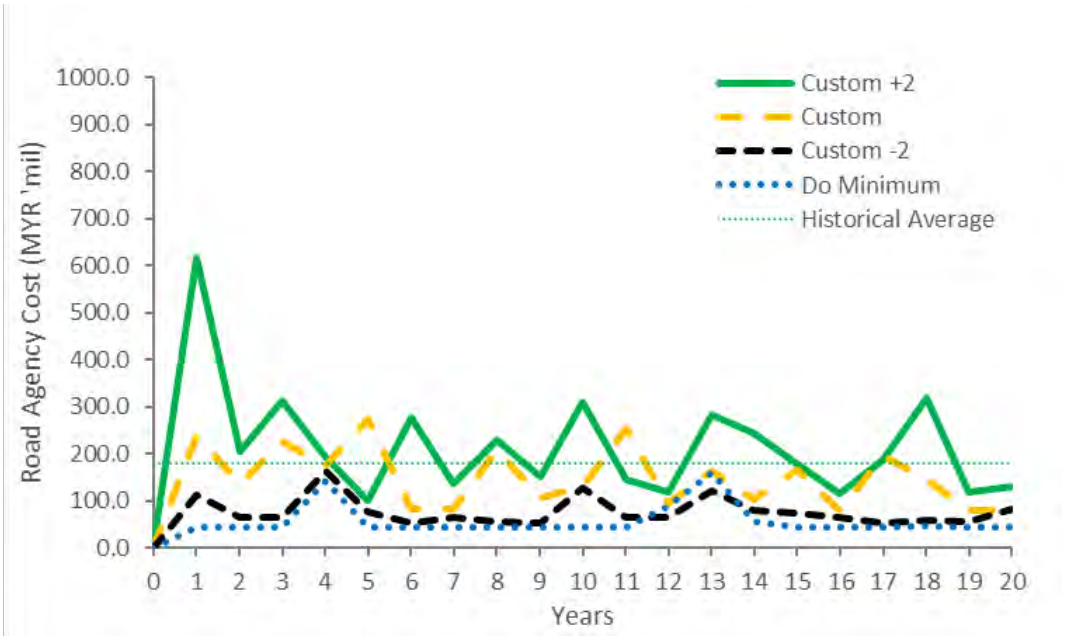


Figure 10.6 Distribution of road agency cost based on Treatment-Based Strategy

Table 10.3 Road agency cost comparison based on the Treatment-Based Strategy

Budget Scenario	Total (MYR 'mil)	Yearly Average (MYR 'mil)	*Cost Difference
Custom +2	4374.5	218.7	21.5%
Custom	3030.5	151.5	-15.8%
Custom -2	1564.5	78.2	-56.6%
Do Minimum	1166.4	58.3	-67.6%
*Historical Average	3600.0	180.0	0.0%

Figure 10.7 shows the effect of Treatment-Based Strategy on road network roughness. The Custom +2 Standard has managed to reduce the average roughness from 4.7 m/km to 2.6 m/km in Year-3. The average roughness continues to be around the same condition between 2.6 m/km to 2.8 m/km until the end of the analysis. For the Custom Standard, the average roughness has gradually reduced from 4.7 m/km to 3.2 m/km in Year-5. Towards the end of the analysis, the average roughness has gradually increased to almost its original condition. As aligned with its budget strategy, the Custom -2 Standard has recorded depreciation in condition with the average roughness pattern almost identical to the Do Minimum Standard. This may happen due to the magnitude of the budget rather than the customised strategy which targeted to minimise the 3-star and to reduce the gap between the higher road hierarchy and the lower ones.

From **Figure 10.8**, the average Star Rating for the Custom +2 and Custom Standard recorded a significant increase from 2.8 to around 3.7 in Year-5/6 and slowly decrease due to the effects of road safety degradation towards the end of the analysis. For the Custom -2 Standard, even though the average roughness has increased far above the maximum target roughness, the average Star Rating has climbed up beyond the target Star Rating from 2.8 to 3.5 in Year-5. The average Star Rating for the Custom -2 Standard is stagnant from this point towards the end

of the analysis. This possibly happens due to the treatment-based prioritisation that helps to strategise the treatment application and tackle the problematic areas.

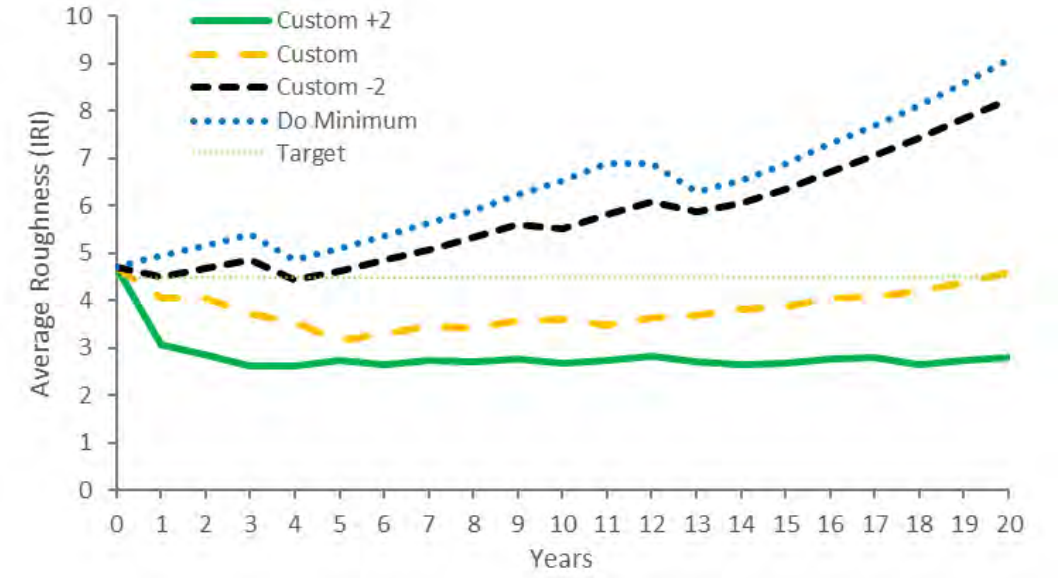


Figure 10.7 Effect of Treatment-Based Strategy on road network roughness

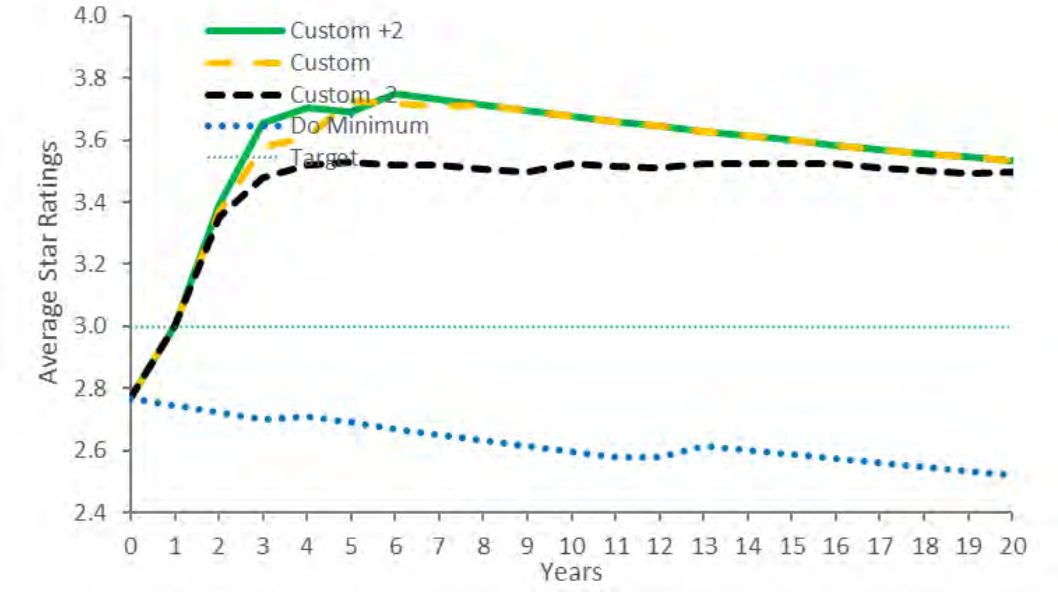


Figure 10.8 Effect of Treatment-Based Strategy on road network safety

In terms of cost, the yearly average cost of the Custom +2 Standards is MYR218.7 million, far exceeding the historical average of MYR180.0 million by 21.5%. However, the yearly average cost of the Custom and Custom -2 Standards is MYR151.5 million and MYR78.2 million respectively within the historical average. As an overall performance, all of the implementation standards in the Treatment-Based Strategy have achieved the minimum target of average Star Rating but Custom -2 Standards fails to reach the target for road condition. The selection of this analysis option has proved that the treatment-based prioritisation method works successfully to tackle road safety issues quickly.

10.5 Impact of Average Budget Strategy (Case III)

Figure 10.9 Figure 10.6 shows the distribution of road agency cost based on the Average Budget Strategy (Case III) and **Table 10.4 s**hows the cost comparison for each standard. From **Figure 10.9**, it is shown that the Very High Standard has opted a high-cost rehabilitation works at the start of the analysis followed by various high-cost periodic maintenance throughout the analysis. The Medium Standard has included four cycles of major maintenance with one high-cost rehabilitation works at the start of the analysis followed by three major cycles of periodic maintenance throughout the analysis. Conversely, the Very Low Standard implemented a very low maintenance budget with four cycles of rehabilitation works throughout the analysis.

Figure 10.10 shows the effect of the Average Budget Strategy on road network roughness. The Very High Standard has managed to reduce the average roughness from 4.7 m/km to 2.4 m/km in Year-3. The average roughness continues to be around the same condition between 2.5 m/km to 2.7 m/km until the end of the analysis. For the Medium Standard, the average roughness has gradually reduced from 4.7 m/km to 2.7 m/km in Year-4 and remain around the same value towards the end of the analysis. Suitable with its budget strategy, the Very Low Standard has recorded depreciation in condition with the average roughness pattern almost identical to the

Do Minimum Standard. This may happen due to the selection of strategy and the magnitude of the budget which is very low.

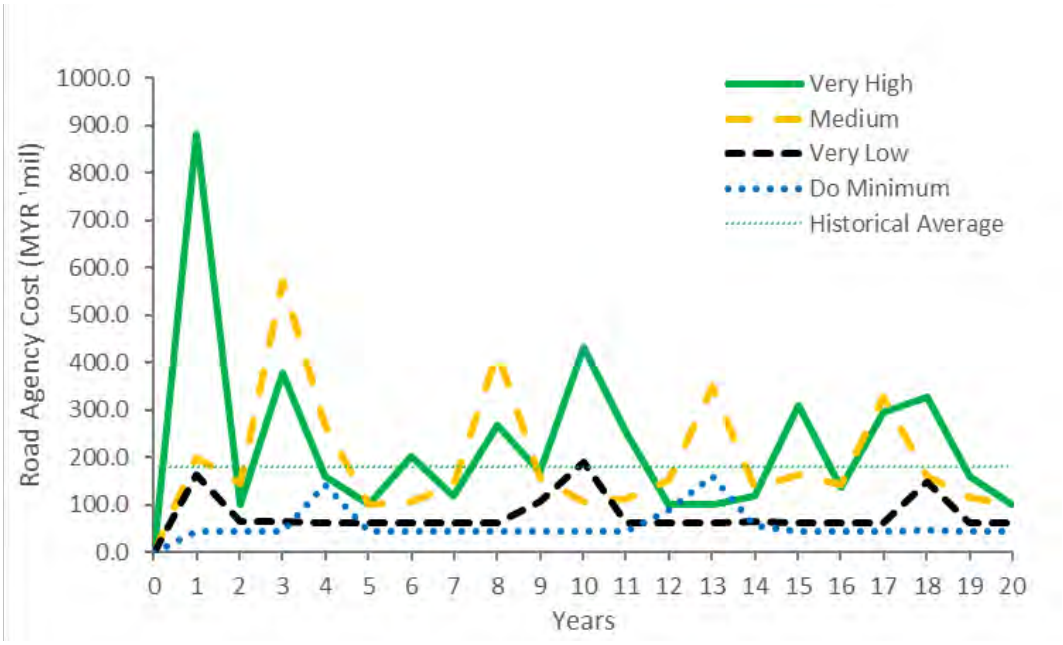


Figure 10.9 Distribution of road agency cost based on Average Budget Strategy

Table 10.4 Road agency cost comparison based on the Average Budget Strategy

Budget Scenario	Total (MYR 'mil)	Yearly Average (MYR 'mil)	*Cost Difference
Very High	4713.7	235.7	30.9%
Medium	3990.7	199.5	10.8%
Very Low	1628.6	81.4	-54.8%
Do Minimum	1166.4	58.3	-67.6%
Historical Average	3600.0	180.0	0.0%

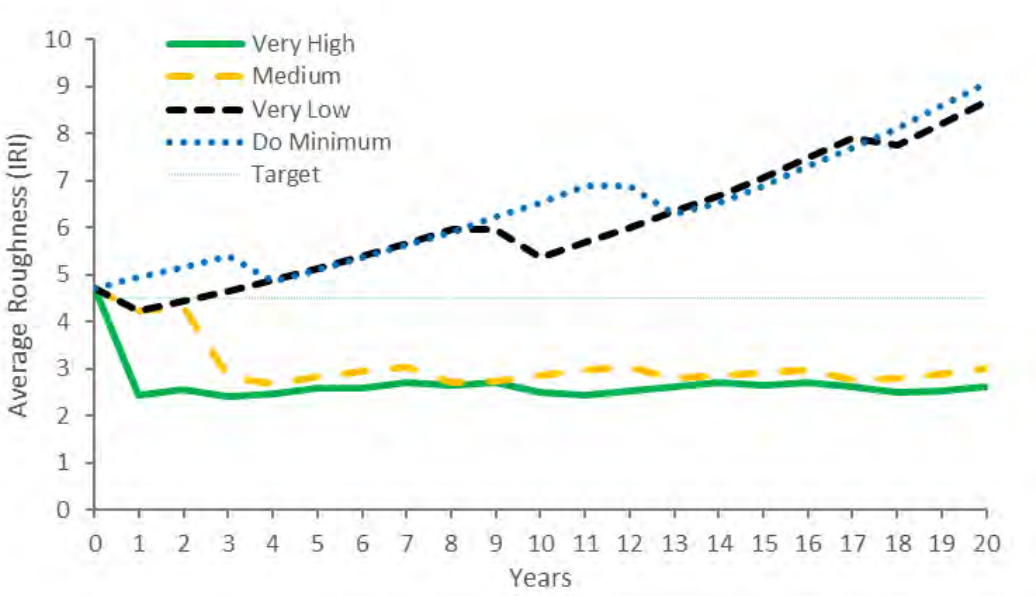


Figure 10.10 Effect of Average Budget Strategy on road network roughness

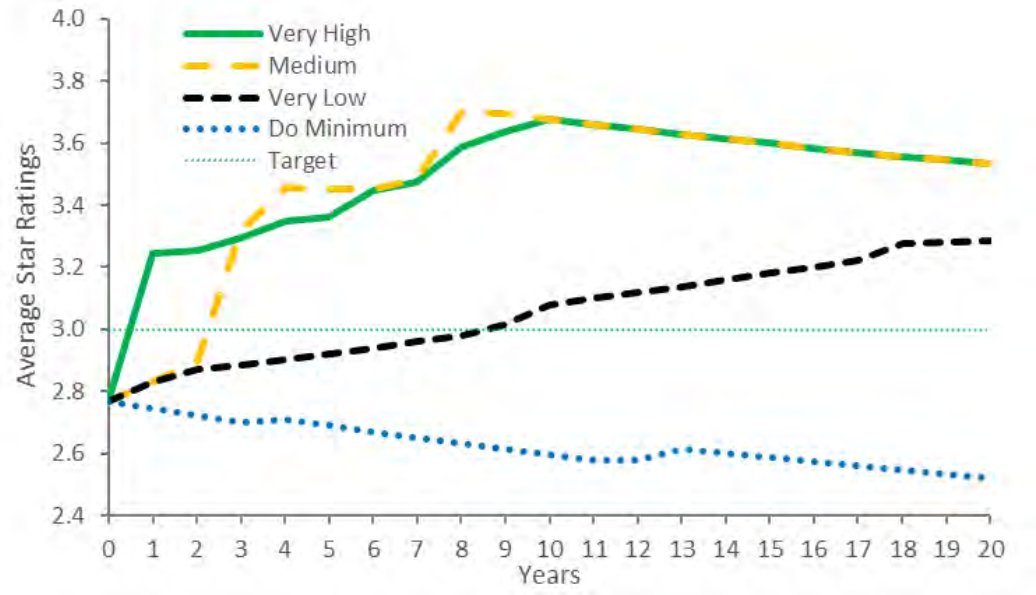


Figure 10.11 Effect of Average Budget Strategy on road network safety

From **Figure 10.11**, the average Star Rating for the Very High and Medium Standard recorded a significant increase from 2.8 to around 3.7 in Year-5/6 and slowly decreased due to the effects

of road safety degradation towards the end of the analysis. For the Very Low Standard, even though the average roughness has increased far above the maximum target roughness, the average Star Rating has gradually increased from 2.8 to 3.3 at the end of the analysis. The increment is very slow which took 10 years to reach the minimum target Star Rating. It is important to note that this strategy complies with the minimum road safety requirements, which is mainly contributed by the implementation of road safety countermeasures and not from the maintenance works.

In terms of cost, the yearly average cost of the Very High Standards is MYR235.7 million, far exceeding the historical average of MYR180.0 million by 30.9%. However, the yearly average cost of the Medium and Very Low Standards is MYR199.5 million and MYR81.4 million respectively, which are far below the historical average. As an overall performance, all of the implementation standards in the Average Budget Strategy have achieved the minimum target of average Star Rating but the Very Low Standards fails to reach the target for road condition. This analysis option has proved that the implementation of road safety countermeasures plays a significant role in increasing the road safety rating.

10.6 Economic Analysis

From the above evaluation of the integrated model, they are assessed in terms of compliance to three technical aspects which are cost, road condition and road safety. The compliance with the cost is divided into three budget range as compared to the historical expenditure record and categorised as Good (< ±20%), Poor (±20%-40%) and Bad (>±40%) as shown in **Table 10.5** and **Figure 10.12**. Compliance with the road condition and road safety are assessed whether the implementation strategy meets the minimum target of average roughness = 4.5 and average star rating = 3.0 respectively.

Table 10.5 Technical compliance

Budget Scenario	Yearly Average (MYR 'mil)	*Cost Difference	Compliance		
			*Cost	Condition	Safety
Optimal +2	233.5	29.7%	✓✓	✓	✓
Optimal	221.4	23.0%	✓✓	✓	✓
Optimal -2	174.0	-3.3%	✓✓✓	✓	✓
Custom +2	218.7	21.5%	✓✓	✓	✓
Custom	151.5	-15.8%	✓✓✓	✓	✓
Custom -2	78.2	-56.6%	✓	×	✓
Very High	235.7	30.9%	✓✓	✓	✓
Medium	199.5	10.8%	✓✓✓	✓	✓
Very Low	81.4	-54.8%	✓	×	✓
Do Minimum	58.3	-67.6%	✓	×	×

✓✓✓ : < ±20% ✓✓ : ±20%-40% ✓ : >±40% (compare to historical average)

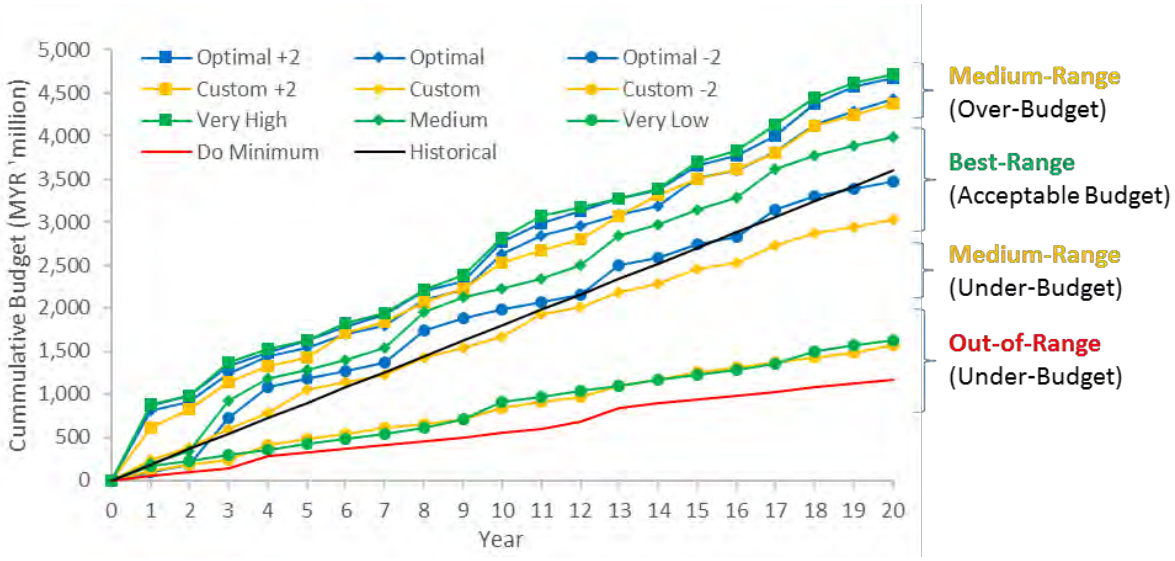


Figure 10.12 Cumulative budget range between standards

From **Table 10.5**, it is shown that all standards have passed the minimum target road safety rating of 3-star. However, some standards such as the Custom -2 and Very Low Standard are unable to reach the target road condition of 4.5 m/km. Therefore, the cost aspect of the analysis

may be used as the concluding decision-support parameter. The Do-Minimum standard is not compared as it is considered the Base Scenario which will be implemented with a basic minimum allocation.

From **Figure 10.12**, it may be suggested that the cost among all standards can be divided into three budget range categories. Therefore, it may be concluded that the acceptable budget range within the historical budget at around ±20% is the best option, between ±20-40% is mid-range and more than ±40% is out of the range. Based on this analysis, the best three standards to be implemented are the Optimal -2, Custom and Medium Standard. The ultimate decision may be decided based on the available budget or the life-cycle analysis of these three standards.

10.7 Conclusion

Chapter 9 and **Chapter 10** have presented the ideal model and the proof-of-concept for the integration of road management and road safety appraisal model. The integration model has considered all the submodels developed for this study. Three case studies have been designed according to the capability of the Road Network Evaluation Tools (RONET) to analyse the available scenario. Based on the analysis, the concurrent effect of road maintenance works and road safety countermeasures can be integrated and evaluated. The analysis has been carried out based on the life-cycle analytical framework which also includes the Road Safety Degradation Model and the Countermeasure Effects Model. Three implementation strategies have been suggested as the result of the economic analysis.

CHAPTER 11

DISCUSSION

11.1 Introduction

In this chapter, the overall approach and findings from this research will be discussed. This chapter will be presented as an explanation of all the judgements and findings throughout the development of this research. It will also discuss the implication of the research findings to the body of knowledge related to the overall road asset management framework. The issues and challenges faced throughout this research will also be shared together with the limitations of the work carried out to date.

In the early stage of this thesis, it was demonstrated that there is a big gap between the most advanced road asset management and road safety investment appraisal model. This chapter will discuss all the findings from the research to assess the progress of closing the gap between these two models.

11.2 Closing the Gap Between Two Models

From the in-depth review of both road asset management and road safety models based on their manual and methodology facts, it has been identified that they differ in terms of five aspects such as inventory data, intervention level, treatment options, economic analysis and prioritisation approach. The differences have been presented in **Chapter 2** and further discussed in **Chapter 3**. However, in terms of their overall functionality, they differ significantly in their analytical framework. As an advanced investment appraisal model, the

road asset management model applies life-cycle cost in the economic analysis. Conversely, the road safety model applies a comparative pre and post (before and after) economic analysis which may not reflect the dynamic condition of the asset that is characterised by constant change. Therefore, this research has developed a protocol framework that may be used to assess the life-cycle of road asset in terms of road safety condition and ultimately integrate the road safety aspect into the road asset management investment appraisal model.

As adopted in many road asset management models, a couple of previous studies have explored the main contribution of pavement properties towards road safety performance. To explore this from a broader range of road asset rather than pavement properties, this research has explored the ability to assess the contribution of overall road asset towards road safety performance. For the overall approach, this research has considered the fundamental effects of road safety level contributed by groups of road attributes.

The effects of road attributes changes have been explained in this research in **Figure 3.1**. It is well acknowledged that road deterioration and road works will simultaneously decrease and increase the road condition. In addition, a similar concept is used to distinguish the evaluation of road safety performance. This fundamental concept has been successfully used in this research to assess the road safety level variation affected by road deterioration and road works.

11.3 Method of Road Safety Analysis

The methodology to predict the future road condition has long been used by the more advanced road management model. For this research, a similar approach has been used to predict the future road safety level. However, it has never been used to predict the future road safety level. Therefore, the prediction model needs to be developed and calibrated to simulate the common pavement prediction model.

A new equation has been derived from this method by introducing new parameters, for instance, road safety rating decrement due to deterioration (*dRSR*) and road safety rating increment due to countermeasure effects ($dRSR_{CE}$). By introducing these parameters, a methodology to evaluate road safety performance with a measurable parameter may be achieved.

Furthermore, the newly introduced evaluation method has opened up an opportunity to formulate four prospects of research questions as listed in **Table 3.2**. The research questions have been rigorously tested in this research using a newly developed analytical protocol seeking to integrate road management and road safety. In this research, the research questions are divided into four stages of analysis. The first stage is carried out in the Road Safety Degradation Model. From this analysis, a road safety prediction model namely the Road Safety Degradation Model has been developed. The second and third stage is carried out in the Countermeasure Effects Model. From this analysis, the Countermeasure Effects Index (CEI) has been developed and all the road safety countermeasures have been categorised based on their work type. The fourth stage is carried out in the Prototype Model. This analysis shows that a concurrent economic analysis can be done in terms of road condition and road safety to prioritise road management and road safety programmes. The successful application of this protocol demonstrates that the aim and objectives of this research have been achieved.

11.4 Road Safety Assessment Tools

This research has looked into the effects of roadworks in eliminating or reducing the accident risk contributed by road infrastructure design. For the first time, the International Road Assessment Programme (iRAP) has been used as the road safety assessment tool to evaluate road deterioration and countermeasure effects on road safety based on road infrastructure design. The iRAP has developed the Star Rating Score (SRS) to determine the level of road

safety in terms of iRAP Star Rating by evaluating the likelihood and severity of accident contributed by road attributes. The iRAP methodology has been chosen to carry out this task because it has increasingly been used to assess the road safety performance of the existing road around the world and is highly supported by the World Bank.

The iRAP Star Rating Score is calculated by the summation of Crash Type Score from every four occupants namely Vehicle Occupant, Motorcycle Occupant, Bicycle Occupant and Pedestrian. However, only Vehicle Occupant has been considered in this model to limit the scope of the research. If the framework of this model is fully developed, it may be easily extended to the other occupants in future.

It has been decided that only four out of six crash types is considered in the analysis as shown in **Figure 4.3**. In this case, Intersection Score and Property Access Score have been dropped out by assuming that the selected road network consists of one continuous road without any intersection or property access. However, the effects contributed by the Intersection Score and Property Access Score may be included in the Star Rating Score by changing the property of other road attributes. In this way, the basic unit of analysis in terms of iRAP Star Rating may be introduced as discussed later in **Chapter 5.**

In this case, the basic unit of analysis represents a homogeneous road section, which in terms of road attributes and road safety level, is a generic road section that has equivalent design standard and road safety level. Commonly, a basic unit of analysis is based on physical attributes and condition. It is the first time that the physical attributes are paired with road safety level as the basic unit of analysis. In this instance, the iRAP Star Ratings, which were initially formed by sets of physical attributes and road safety level, are associated with the equivalent local road geometric design standard.

Further investigation has been carried out to identify the sensitivity of the road attributes that may be subjected to change due to fluctuating asset condition over time. In this case, geometric parameters such as lane width and curvature are not included in this model but only those which have deteriorated over time such as road condition and road markings are considered. It was found that only five road attributes are dynamic and may be subjected to change due to asset deterioration as shown in **Table 4.1**. The rest of the road attributes are supposedly constant over time or could be the geometric parameters of road asset.

11.5 Road Asset Management Tools

The Road Network Evaluation Tools (RONET) has been chosen as the road asset management tool to evaluate the performance of road asset. This model was chosen because of its capability to carry out the analysis based on the fundamental principles used by the most advanced road management appraisal model (i.e. HDM-4) in a simplified manner. The tool is in the Microsoft Excel spreadsheet version and can be used by anyone with minimal training. It is readily available to download from the World Bank website.

The RONET adopted a common cracking progression model for bituminous pavement as shown in **Figure 4.4**. In general, the progression model consists of five condition levels. For this research, a similar condition level is adopted because the road safety level in the International Road Assessment Programme (iRAP) also consists of five condition levels. In this way, it was easier to compare the relationship between the progression model of the two models.

11.6 Road Safety Degradation Model (RSD)

One of the submodels that have been introduced for the first time in this research is the Road Safety Degradation Model (RSD). The Road Safety Degradation Model is used to predict the

degradation rate of road safety rating affected by the deterioration of road assets. This submodel is one of the important components that will provide the methodology to answer the first research question (RQ1) related to the effects of road deterioration on the road safety level.

As previously mentioned, the International Road Assessment Programme (iRAP) Star Ratings have been used as the basic unit of analysis. A basic unit of analysis is used to break down the network into a successively smaller section. Each group of the section may be uniquely defined based on their uniformity in terms of road attributes, physical characteristics or geometric standard. Interestingly, in this research, the unit of analysis is recognised based on the five categories of road safety level in terms of iRAP Star Rating as summarised in **Table 5.1**. In this way, each Star Rating can be uniquely tested with a desirable standard.

In this research, the Road Safety Degradation Model has been developed in a way that resembles a common pavement deterioration prediction model. This is aligned with the discovery of the five sensitive attributes namely Shoulder Rumble Strips, Centreline Rumble Strips, Delineation, Road Condition and Skid Resistance/Grip, which are placed within the pavement region. Even though it has been expected that road safety-related attributes may extend beyond the pavement region, it was found that the sensitive road attributes are contained within the road pavement related properties.

A sensitivity analysis has been carried out to test the possible outcome for the selected road attributes. From this analysis, it has been identified that only two attributes, namely the Skid Resistance/Grip and Road Condition, are the most significant parameters to be included in the Road Safety Degradation Model. The other three attributes, namely Shoulder Rumble Strips, Centreline Rumble Strips, Delineation are found out to be insignificant to reduce the Star Rating.

In line with the road asset deterioration model, the other road assets such as road furniture, road signages, drainages and geometric attributes are insignificant to be included in the model. The consideration of these items would require life-cycle models which are not readily available. In normal condition, with minimum routine maintenance, most of these attributes may last longer than the analysis period of 20 years considered in this research.

The condition properties of the Skid Resistance/Grip and the Road Condition may produce nine deterioration combinations which may be arranged based on their magnitude to reduce the road safety level. The magnitude is calculated based on the Star Rating Score (SRS) difference between the best combination and a poorer combination. The magnitude is used to classify the deterioration combinations into five categories of Road Safety Degradation Index (RSDI) namely Very Good (E1), Good (E2), Fair (E3), Poor (E4) and Very Poor (E5).

The characteristics of the Road Safety Degradation Index is in line with the sigmoidal curve for the initiation and progression phases of distress as adopted in the HDM-4 and also the cracking progression model as adopted in the Road Network Evaluation Tool (RONET). Based on the development of the Road Safety Degradation Index, it has become strongly evident to suggest that the Road Safety Degradation Model may adopt a similar pattern of the sigmoidal curve. The magnitude of the degradation relative to time is beyond the scope of this research. However, this research has considered a simple Markov probability transition matrix to predict the magnitude of the deterioration model.

11.7 Countermeasure Effects Model (CE)

The other submodel that has been introduced in this research is the Countermeasure Effects Model (CE). The Countermeasure Effects Model is identified by comparing the iRAP Star Rating before and after the treatment. Fifteen possible countermeasure effects have been

identified, which can be categorised into five Countermeasure Effects Index (CEI) based on the magnitude of their effects.

The major challenges to develop the Countermeasure Effects Model is to incorporate the Countermeasure Effects Index into every roadwork activities. To establish this integration, intervention criteria have been formulated based on the iRAP Star Rating. Based on this formula, the Star Rating is used to identify the magnitude of the proposed countermeasures. The priority of each countermeasure is ranked based on the extensive and the cost range of the treatment.

A sensitivity analysis has been carried out to evaluate the magnitude of countermeasure effects contributed by each roadworks type. A unique evaluation procedure has been designed to carry out the sensitivity analysis and evaluate the magnitude of countermeasure effects. For this purpose, the evaluation is carried out based on the standard deviation (σ) of the road attribute risk factors. The weighting of all road attributes is calculated with reference to the standard deviation to assign a ranking of the road attributes based on their sensitivity to the Star Rating Score. For each countermeasure, the total value of the weighted risk factor is calculated based on the related scope of work. The total value of the weighted risk factor will determine the countermeasure classifications and rank.

The sensitivity analysis clearly grouped all the maintenance roadworks and road safety countermeasures into five categories based on the value of the weighted risk factor. The factor may also be used to rank the countermeasure based on their contribution to road safety performance. The grouping approach has successfully incorporated all the road works and road safety countermeasure into an integrated list of the Countermeasure Effects Index (CEI) as shown in **Table 6.7**.

This is a major achievement towards the integrated model of road safety and road management investment appraisal. The Countermeasure Effects Index may provide the answer to the second research question (RQ2) related to the effects of road maintenance works on the road safety level. The Countermeasure Effects Index may now be used to identify the effects of road works in terms of road safety performance.

11.8 Correlation Between Road Safety and Road Condition

From the data collection exercise, a preliminary condition assessment was carried out to determine the existing condition of the road network in terms of roughness and road safety Star Rating. Based on the condition assessment, the roughness data and road safety Star Rating data have been tested to determine the correlation between their relative condition. The correlation is calculated by the square of the Pearson Product-Moment Correlation Coefficient, *r*, which measures the correlation or linear association between two sets of variables.

The result of the correlation analysis is shown in **Table 8.6**. From the analysis, only 3-Star and Fair condition significantly correlate to each other with R^2 of 0.9938. For the other pairs, the R^2 is between 0.5624 to 0.8900. However, if both higher ratings and lower ratings are grouped together, for instance, the 1-Star/2-Star and 3-Star/4Star, the correlation with the respective road condition, namely Very Poor/Poor and Good/Very Good, the R^2 value will increase significantly between 0.9116 to 0.9425.

Several conclusions may be drawn from this result. Firstly, the middle rating parameter, 3-Star and Fair condition can be considered highly correlated to each other. Conversely, the other four condition pairs on higher and lower sides do not significantly correlate to each other. However, the correlation will increase significantly by grouping each two higher ratings and lower ratings together. Therefore, it can be concluded that roads with 1-Star/2-Star and 3-Star/4-Star safety

rating may fall within the Very Poor/Poor and Good/Very Good condition respectively at a disproportionate amount. For example, the total amount of 1-Star/2-Star roads may be equal to Very Poor/Poor roads. However, the proportion of 1-Star roads to Very Poor roads may be unequal. This is also the case for the other pairs.

11.9 Characteristics of Road Safety Degradation

Based on the correlation between road safety and road condition, it has provided some vital hints related to the relationship characteristics of road deterioration and road safety degradation. This has also provided a better understanding of the theoretical development of the road safety degradation initiation and progression phases as shown in **Figure 5.3**. Considering this connection and also the roughness classification based on the affected area as shown in **Table 8.7**, the progression phases of roughness may be linked to road safety degradation as shown in **Figure 8.8**.

Based on **Figure 8.8**, a group of equations has been derived to determine the rate of the relationship of road safety and road condition. The derived equations have also been tested in terms of their correlation between road safety and road condition. Based on the result, it can be concluded that the relationship is strongly correlated to predict either road safety and road condition except for the prediction of the Poor condition from 1-Star road which recorded an insignificant value of $R'^2 = 0.4151$.

From the derived formula, the length of road for any road safety Star Rating can be predicted based on the respective road condition or vice versa. Therefore, this methodology may also be used to carry out the data imputation to replace missing data with substituted values as well as a prediction model for road safety degradation. The data imputation process may be considered for a road network that lacks either one of the road condition or road safety data. With this

development, this model should be considered as a new prediction model for the road safety degradation that linked road condition in terms of roughness deterioration with road safety depreciation.

Based on the Road Safety Degradation model, the road safety performance of the selected network was predicted. To ensure that the annual deterioration rate represents the real deterioration behaviour appropriate for the existing road network, numerous deterioration rate conditions have been considered, for instance, constant rate, proportional rate and normally distributed rate as shown in **Figure 9.12**. The constant rate is appropriate for the existing network where deterioration occurs randomly throughout the network. The proportional rate and normally distributed rate are more appropriate for new pavement when the deterioration occurs at a slower rate at the beginning and more rapid either towards the end or at the middle of the analysis period.

Considering the 20-year period of analysis, an annual deterioration rate of 5% is appropriate for the pavement life-cycle. Some adjustments have also been done to the annual road safety degradation rate to reflect the change rate difference between each road safety rating. As a result of these conventions, the outcome of road safety degradation as derived from the preliminary condition assessment is shown in **Figure 9.13**.

11.10 Semi-Empirical Integration Model

It has been discussed in **Chapter 5** that the condition projection method can be grouped into two main classes namely probabilistic and deterministic. A probabilistic model applies a range of possible condition in terms of a probability function to predict the condition. On the other hand, a deterministic model predicts the condition projection based on a precise value of mathematical functions derived from observed or measured deterioration.

In this research, the condition projection method used for the road safety model was developed based on a probabilistic model as discussed in **Chapter 5** and **Chapter 8**. Conversely, the road asset condition projection is carried out based on the pavement mechanistic-empirical approach using the deterministic model as adopted in the Road Network Evaluation Tools (RONET) or some other models such as the Highway Development and Management Tools (HDM-4). Therefore, the integration of these two models has combined two condition projection methods into a semi-empirical model that contains a hybrid process of the probabilistic and deterministic method.

The integration has been carried out in a parallel assessment to determine the road condition and road safety performance. The road condition assessment is carried out using the automated RONET analysis tool to answer the third research question (RQ3) related to the effects of road safety countermeasures on road condition. On the other hand, the road safety assessment has to be carried out in a step-by-step "manual" manner using the Microsoft Excel spreadsheet because there is no available analysis tool that is appropriate to perform this analysis. Formula to calculate the Average Star Rating (ASR) has been suggested at the end of **Chapter 9** to aggregate the multiple Star Rating into a simplified but expressive value.

11.11 Application of the Integrated Model in Malaysia

This research has been carried out based on the data that has been collected in Malaysia. Several factors supported the selection of Malaysia as the study area. One of the main reason is the availability of data that covers both road asset management and road safety requirements. Furthermore, Malaysia is a developing country that has one of the developed road transport infrastructure networks.

In terms of road maintenance activity, Malaysia is performing well above the minimum standard suggested by the World Bank. Annually, the road authority at the local and Federal level receives a substantial amount of road fund for the development and management of road infrastructure. Despite all these positive factors, the accident statistic in Malaysia can be considered high compared to most developed countries. Therefore, with all these reasons, it can be foreseen that the development of this model around Malaysia background may benefit more developing countries as well as developed countries.

Three case studies have been carried out based on the available implementation strategies to predict the effects of different budget scenario within a 20-years period of analysis. The analysis has provided the answer to the fourth research question (RQ4) about the effects of a different roadworks implementation strategy on the road condition and road safety level. The execution of three case studies namely the *Benefit-Cost Ratio Strategy,* the *Treatment-Based Strategy* and the *Average Budget Strategy* will produce 19 standards or road work budget scenario with each case study is presented by seven or eight different standards including the Do Minimum and Do Nothing which are equal for each of the case studies.

In general, the case studies have successfully demonstrated the integration of road safety and road management investment appraisal model in a parallel assessment of road condition and road safety level projection. It has been demonstrated that the road condition and road safety level can be projected in a parallel assessment as presented in **Chapter 10** of this research. The overall findings of the economic analysis are summarised in **Table 10.5**.

The selection of budget scenario should comply with the target objectives of a maximum of 4.5m/km average roughness in terms of the International Roughness Index (IRI) and should be a minimum of 3-Star for road safety rating. In terms of budget limitation, it is suggested that the selection of the budget scenario should be within the historical average with a tolerance of

around 10%. Based on the result of the economic analysis, three implementation strategies complied with the target objectives. The three implementation strategies that achieved these targets are the Optimal -2 Standard, Custom Standard and Medium Standard.

Based on the economic analysis, the outcome of this research is highly recommended to be implemented directly in Malaysia. It is because this research has been developed and configured based on local surroundings and requirements. Considering the average historical budget of MYR180 million, it is highly recommended that the Optimal -2 Standard is selected because the budget difference is about 3% less than the historical average.

The implementation of the outcome of this research in Malaysia will directly benefit the road users at large. With the implementation of the recommended standard, it is expected that road user cost in Malaysia may reduce after three years when the target objective on road condition with 4.5m/km average roughness is achieved. It is also expected that the accident and fatality rate in Malaysia will reduce significantly after four years when the target objective of the average rating of 3-Star is achieved. However, the road authority may need to consider the additional budget requirements between two to three times above the average historical budget to carry out four cycles of major rehabilitation and periodic maintenance throughout the analysis period.

11.12 Transferability of the Model

The integrated road safety and road management investment appraisal model that has been developed and presented in this research is a generic framework model. It is transferable and may be used by any road manager in developed or developing countries. For the road management part, a basic system calibration needs to be done to suit the local condition. The calibration procedure is available in the Road Network Evaluation Tools (RONET) user guide.

For the road safety part of the model, a general adaptation needs to be carried out to configure the homogeneous road sections based on local standards to match the equivalent Star Ratings. The adaptation can be done based on the approach presented in **Chapter 5**. However, it is practical to assume that the existing homogeneous road sections are applicable to most country as the standards used are equivalent to international standards.

11.13 Issues and Challenges

11.13.1 Data Collection

One of the main issues faced in this research is the availability of data. The data collection of road assets is very expensive because it uses a high-speed road surface profiler which is normally equipped with high accuracy data collection devices and cameras. Therefore, this research relies entirely on existing data or secondary data. The problem is getting worse as the integration may require one set of data for each road asset and road safety model. However, this research has presented in **Chapter 8** the methodology to carry out data generation for road condition or road safety based on a calibrated road safety prediction model.

11.13.2 Lack of Data

Even though many countries have been implementing road asset management system in their road management programme and the number of countries that are involved in road safety management system is increasing, it has been anticipated that some countries may lack either one aspect of the data. Therefore, it has been presented in **Chapter 8** the general process of generating artificial data to complement the lack of data. The artificial data can be generated based on the **Eq. 8.2** – **Eq. 8.11** that have been developed. For this purpose, the process of generating data has been developed based on the relationship between roughness and road safety condition as previously presented in **Chapter 5**.

11.14 Limitations of Research

In **Chapter 4**, certain considerations have been highlighted as an additional measure to adjust the scope of this research within the controllable limit. Firstly, the life span of each countermeasure considered in this research was not within the scope of this research. Therefore, the available standard from the International Road Assessment Programme (iRAP) Road Safety Toolkit was used to ensure the selection of countermeasure for this research is carried out based on a certain standard. Other than the life span, the toolkit may provide all important information related to available countermeasures such as cost range and effectiveness.

Secondly, it is identified in the iRAP Star Rating Score analysis that a road may become safer at a lower operating speed regardless of the geometric design. Therefore, a considerably high -speed is set to each Star Rating to ensure that it reflects the appropriate Star Rating and geometric design of the road. In this way, road safety analysis is carried out based on a similar basis.

As previously discussed, the scope for this research is limited to consider only the Vehicle Occupant in its model. Other road users such as Motorcycle Occupant, Bicycle Occupant and Pedestrian are not considered because a longer period will be needed to cover these areas. However, if the framework of this model is fully developed, it may be easily extended to the rest of the occupants in the future.

The demonstration of how the artificial data for road condition and road safety are generated based on the Road Safety Deterioration Model is shown in **Chapter 8**. The accuracy of this data is subject to the calibration method that has been presented in **subchapter 9.5**. Even though the model has been validated, the accuracy of the prediction model needs to be further developed.

Finally, the limit of this research is controlled by the capabilities of both selected road management and road safety models. Both selected models were designed to analyse the appropriate data for their intended usage. Therefore, they both have limitation in analysing parameters from another model. For instance, the road management model may analyse road deterioration and roadwork effects only. This limitation has been tackled by manual adjustment. The proposed roadworks and road safety countermeasures have been manually transferred to the other model. The outcome of the treatment has also been evaluated manually.

It has been purposely decided that a new integrated tool will not be developed in this research. It is to ensure that the integration framework may be used by any available tool accordingly. It is also important to show how the integration is carried out especially the steps taken to assess road safety as an incremental model. However, this approach must not ignore the limitation caused by the capabilities of both models.

11.15 Conclusion

This chapter has presented the overall discussion related to this research. All the major achievements and findings have been discussed in details to clarify the pattern of the result. Issues and challenges are also discussed as a guide for future research. The consideration and limitation of this research have also been highlighted.

CHAPTER 12

CONCLUSIONS AND RECOMMENDATIONS

12.1 Introduction

This chapter is the final chapter presented in this thesis. It will conclude all the eleven chapters that have been previously presented and discussed. The main content of this chapter is the concluding remarks related to the achievement of the aim and objectives of this research. It will also highlight the key findings related to this research. Some recommendations are also suggested for future research to ensure continuous improvement on this model.

12.2 Aim and Objectives Achieved

This research has developed a new methodology for road asset investment appraisal by integrating the road asset management model and road safety model. Two submodels have been developed as a link to integrate between road asset management model and road safety model namely Road Safety Degradation (RSD) and Countermeasure Effects (CE). The methodology has been demonstrated in a parallel life-cycle cost analysis alongside the road condition and road safety assessment using Malaysia as the case study. The model has proven that the road safety model can be integrated with the road asset management model to maximise benefits to road users and stakeholders.

12.3 Conclusions and Key Research Findings

12.3.1 Model Comparison

i. The road asset management appraisal model differs from the road safety model in five major aspects in terms of inventory data, intervention level, treatment options, economic analysis and prioritisation.

ii. The road asset management appraisal model such as the Highway Development and Management Tools (HDM-4) is so advanced compared to the available road safety model especially in terms of economic analysis.

12.3.2 Conceptual Model

i. Road safety performance may also be affected by road deterioration and roadworks.

ii. The effect of road safety level reduction caused by road deterioration is named the Road Safety Degradation in this model.

iii. The effect of road safety enhancement caused by roadworks is named the Countermeasure Effects in this model.

iv. Future road safety performances can be predicted using a similar concept used to predict future road conditions.

v. Road asset management tool such as the Road Network Evaluation Tools (RONET) is used to assess road condition performance in this model.

vi. Road safety assessment tool such as the International Road Assessment Programme (iRAP) is used to assess road safety performance in this model.

12.3.3 Model Development

i. The iRAP methodology is used to calculate the Star Rating Score (SRS) that represents the relative risk of death and serious injury for an individual road user.

ii. The Star Rating Score (SRS) is the summation of Crash Type Scores calculated based on the crash initiation modes and their contributing factors that initiate road accidents.

iii. Only four types of crash initiation modes are considered in this model namely run-off (driver-side), run-off (passenger-side), head-on (loss of control) and head-on (overtaking).

iv. The iRAP Star Rating is used as a homogeneous road section to determine a basic unit of analysis. In terms of road attributes and road safety level, the basic unit of analysis is a generic road section that has equivalent design standard and road safety level.

v. Two attributes are the most significant parameters to be included in the Road Safety Degradation Model (RSD) namely the Skid Resistance/Grip and Road Condition. The rest of the attributes are insignificant in reducing the road safety level.

vi. Road Safety Degradation Index (RSDI) indicates the severity level that can be contributed by Skid Resistance/Grip and Road Condition deterioration combinations.

vii. The Markov probability transition matrix is used to define the probability of an initial safety level that would deteriorate to a particular future safety level.

viii. The iRAP Star Rating is also used as the intervention criteria for road safety project implementation.

ix. In the Countermeasure Effects Model (CE), treatment ranking is set based on the Countermeasure Effects Index (CEI) and comprehensiveness of the treatment scope of the work. The Countermeasure Effects Index was determined from a sensitivity analysis that classifies the countermeasure based on the weighted risk factor. The countermeasure classification is ranked based on five Countermeasure Effects Index namely

Development (C1), Upgrading 1 (C2), Upgrading 2 (C3), Periodic (C4) and Routine (C5).

12.3.4 The Ideal Integration Model

i. The application of this model was carried out based on road condition and road safety assessment data collected in Malaysia.

ii. The road condition and road safety data have been tested to determine the correlation between their relative condition pairing. Only 3-Star and Fair condition significantly correlate with each other. The correlation significantly increased for both higher ratings and lower ratings when they are grouped as the 1-Star/2-Star and 3-Star/4Star relative to the Very Poor/Poor and Good/Very Good condition.

iii. Data generation can be carried out to overcome the lack of either road condition or road safety data.

iv. The integration of road management and road safety models was carried out based on a loose coupling method that is very flexible for integration and less dependent on each other. The integration has combined two condition projection methods into a semi-empirical model that contains a hybrid process of the probabilistic and deterministic method.

v. The incremental analysis procedure was carried out in automatic operation for road condition assessment using the RONET and in manual operation for road safety assessment using Microsoft Excel spreadsheet.

vi. The annual road safety degradation applies the annual deterioration rate of 5% appropriate for pavement life-cycle with some adjustments to reflect the change rate difference between each road safety rating.

vii. The Average Star Rating (ASR) equation is used to aggregate the multiple Star Rating into one simplified but expressive average value.

12.3.5 Proof-of-concept Integrated Model

i. Three case studies were designed to demonstrate the integration model namely the Benefit-Cost Ratio Strategy (Case I), Treatment-Based Strategy (Case II) and Average Budget Strategy (Case III) which have been carried out using the RONET evaluation options namely Optimal Standard, Custom Standard and Equal Standard respectively.

ii. The RONET evaluation has produced 19 standards or road work budget scenario with each case study is presented by seven or eight different standards including the Do Minimum and Do Nothing which are equal for each of the case studies. Only 10 standards are compared and discussed.

iii. The target objectives that have been set are to achieve a maximum of 4.5m/km average roughness in terms of the International Roughness Index (IRI) and should be a minimum of 3-Star for average road safety rating.

iv. Seven implementation strategies significantly achieved the target objectives within the 20-year period of analysis. However, only three strategies, namely the Optimal -2 Standard, Custom Standard and Medium Standard, complied with the budget requirement within the acceptable budget of 20% difference from the average historical budget.

12.3.6 Implementation in Malaysia

i. The outcome of this research is highly recommended to be implemented directly in Malaysia because it has been developed and configured based on local surroundings and requirements.

ii. It is highly recommended that the Optimal -2 Standard is selected because the budget difference is about 3% less than the historical average of MYR180 million.

iii. The implementation of the outcome of this research in Malaysia will directly benefit road users at large by reducing road user costs and reducing accident and fatality statistics in Malaysia.

12.3.7 Challenges and Limitations of Research

i. It has been anticipated that some countries may lack either one aspect of road condition or road safety data.

ii. The process of generating data has been developed in this research based on the relationship between roughness and road safety condition.

iii. A considerably high-speed is set to each Star Rating to ensure that it reflects the appropriate Star Rating and geometric design of the road.

iv. The life span, cost range and effectiveness of each countermeasure considered in this research are based on the International Road Assessment Programme (iRAP) Road Safety Toolkit.

v. The scope for this research is limited to consider only the Vehicle Occupant in its model.

12.4 Recommendations and Future Work

Recommendation for future research are as follows:

i. To investigate the approach used at the programme level and project level analysis;

ii. To develop further the Road Safety Degradation Model based on empirical data;

iii. To carry out sensitivity analysis, systematic validation and calibration of the integrated model;

iv. To use other road management investment appraisal tools such as the Highway Development and Management Tools (HDM-4) instead of the Road Network Evaluation Tools (RONET).

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APPENDICES

Appendix 1 The iRAP Road Attribute Risk Factors

Appendix 2 Vehicle Occupant Star Rating Score Equation Diagram

Appendix 3 Design Standard and Road Classification

Appendix 4 Basic Characteristics of the Homogeneous Road Section

Appendix 5 Star Rating Worked Example

Appendix 6 Summary of Safer Road Treatment (iRAP Road Safety Toolkit)

Appendix 7 Road Accident Statistics in Malaysia (1997-2015)

Appendix 8 iRAP Recommended Countermeasure Programme

Appendix 9 Annual Work Programme

Appendix 10 Road Safety Degradation, dRSR (RSD)

Appendix 11 Road Safety Assessment

Appendix 12 Research Publications, Presentations and Award

Appendix 1 The iRAP Road Attribute Risk Factors

Descriptive Road Attributes

- Coder name
- Coding date
- Road survey date
- Image reference
- Road Name
- Section
- Distance
- Length
- Latitude
- Landmark
- Upgrade cost
- Vehicle parking
- Service road
- Roadworks
- Sight distance
- Intersection quality
- Land use - drivers side
- Land use - passenger side
- Area type

Influential Road Attributes

Roadside

- Roadside severity - drivers side distance
- Roadside severity - drivers side object
- Roadside severity - passenger side distance
- Roadside severity - passenger side object
- Shoulder rumble strips
- Paved shoulder - drivers side
- Paved shoulder - passenger side

Mid-block

- Carriageway
- Median type
- Centreline rumble strips
- Number of lanes
- Lane width
- Curvature
- Quality of curve
- Grade
- Road condition
- Skid resistance / grip
- Delineation
- Street lighting

Intersection

- Intersection type
- Intersection channelization
- Intersecting road volume
- Property access points

VRU and Land Use

- Pedestrian crossing - inspected road
- Pedestrian crossing quality
- Pedestrian crossing facilities - side road
- Pedestrian fencing
- Sidewalk - drivers side
- Sidewalk - passenger side
- Facilities for motorised two-wheelers
- Bicycle facility
- School zone warning
- School zone crossing supervisor

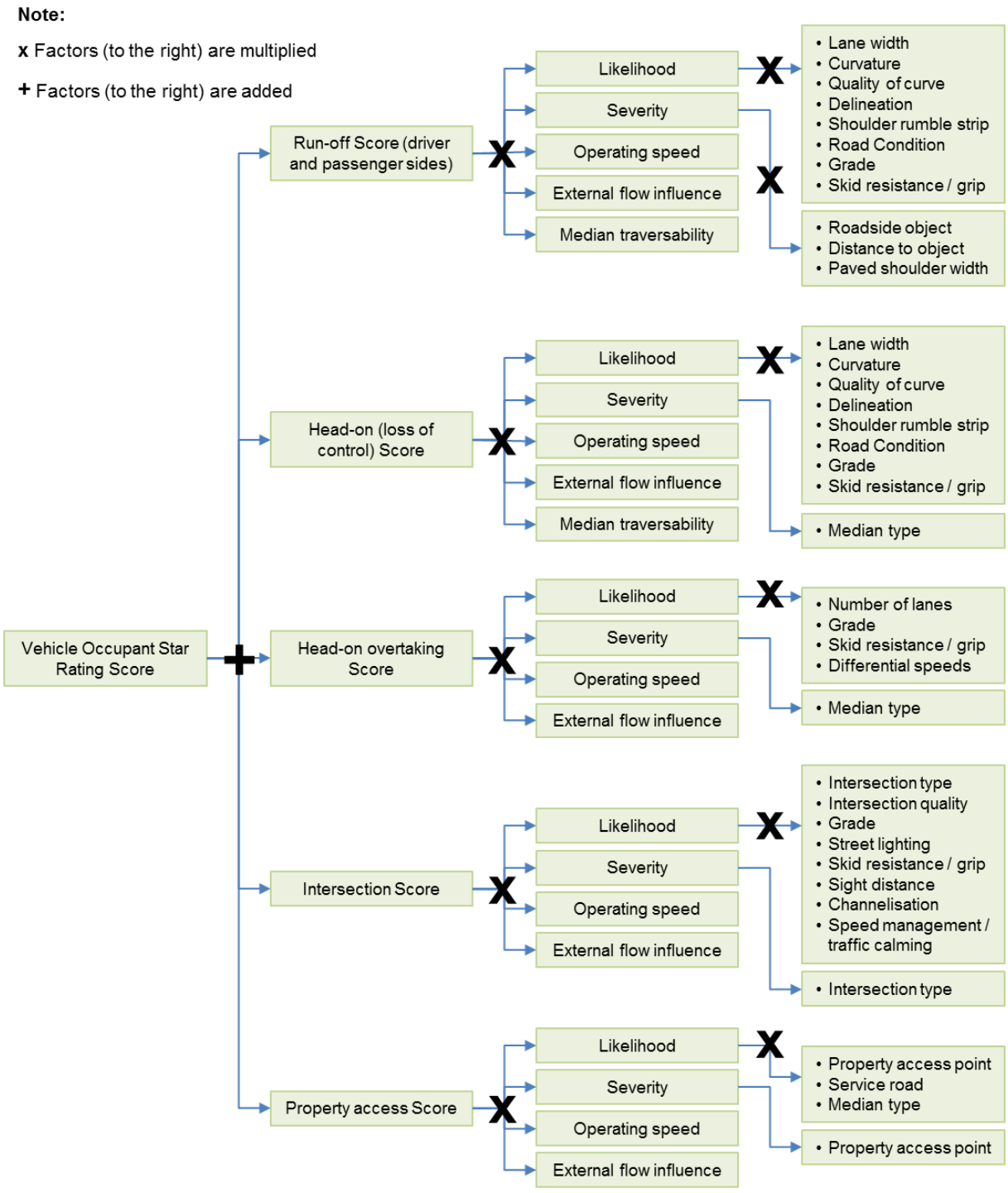
Flow

- Vehicle flow (AADT)
- Motorcycle %
- Pedestrian peak hour flow across the road
- Pedestrian peak hour flow along the road driver-side
- Pedestrian peak hour flow along the road passenger-side
- Bicycle peak hourly flow

Speed

- Speed limit
- Differential speeds
- Speed management / traffic calming
- Operating Speed (85th percentile)

Appendix 2 Vehicle Occupant Star Rating Score Equation Diagram



(Source: iRAP, 2014)

Appendix 3 Design Standard and Road Classification

TABLE 2-3: DESIGN STANDARDS

Area	Road Catagory	Projected ADT					
		All Traffic Volume	> 100,00	10,000 to 3,000	3,000 to 1,000	1,000 to 150	< 150
RURAL	Expressway	R6	-	-	-	-	-
	Highway	R5	-	-	-	-	-
	Primary Road	-	R5	R4	-	-	-
	Secondry Road	-	-	R4	R3	-	-
	Minor Road	-	-	-	-	R2	R1 / R1a
URBAN	Expressway	U6	-	-	-	-	-
	Arterials	-	U5	U4	-	-	-
	Collector	-	-	U4	U3	-	-
	Local Street	-	-	-	U3	U2	U1 / U1a

(Source: REAM, 2002)

TABLE 3-2A : DESIGN SPEED (RURAL) (AMENDED SEPT. 1989)

Design Standard	Design Speed (km / hr)		
	Terrain		
	Flat	Rolling	Mountainous
R6	120	100	80
R5	100	80	60
R4	90	70	60
R3	70	60	50
R2	60	50	40
R1	40	30	20
R1a	40	30	20

(Source: REAM, 2002)

TABLE 3-213: DESIGN SPEED (URBAN) (AMENDED SEPT. 1989)

Design Standard	Design Speed (km / hr)		
	Area Type		
	I	II	III
U6	100	80	60
U5	80	60	50
U4	70	60	50
U3	60	50	40
U2	50	40	30
U1	40	30	30
U1a	40	30	20

(Source: REAM, 2002)

TABLE 5-3 : LANE AND MARGINAL STRIP WIDTH

Design Standard	Lane Width (m)	Marginal Strip Width (m)
R6 / U6	3.50	0.50
R5 / U5	3.50	0.50
R4 / U4	3.25	0.25
R3 / U3	3.00	0.25
R2 / U2	2.75	0.00
R1 / U1	(5.00)	0.00
R1a / U1a	(5.40)	0.00

(Source: REAM, 2002)

Appendix 4 Basic Characteristics of the Homogeneous Road Section

Star Rating	★★★★★	★★★★	★★★	★★	
Star Rating Score	1.52	3.70	9.19	16.67	31.61
Homogeneous Section	High-standard motorway	High-standard rural	Medium-standard rural	Rural road	Low-standard rural
Design Standard	R6	R5	R4	R3	R2
Road Class	Expressway	Highway	Primary Road	Secondary Road	Minor Road
Roadside severity - driver-side distance	5 to <10m	0 to <1m	5 to <10m	1 to <5m	0 to <1m
Roadside severity - driver-side object	Safety barrier - metal	Safety barrier - metal	None	None	None
Roadside severity - passenger-side distance	>=10m	5 to <10m	5 to <10m	1 to <5m	0 to <1m
Roadside severity - passenger-side object	None	Deep drainage ditch	None	None	None
Shoulder rumble strips	Not present	Not present	Not present	Not present	Not present
Paved shoulder - driver-side	Medium (>=1.0m to <2.4m)	Narrow (>=0m to <1.0m)	Medium (>=1.0m to <2.4m)	None	None
Paved shoulder - passenger-side	Wide (>=2.4m)	Medium (>=1.0m to <2.4m)	Medium (>=1.0m to <2.4m)	None	None
Carriageway label	Carriageway A of a divided carriageway road	Carriageway A of a divided carriageway road	Undivided road	Undivided road	Undivided road
Upgrade cost	Low	Low	Medium	Medium	High
Median type	Safety barrier – metal	Safety barrier – metal	Centre line	Centre line	Centre line
Centreline rumble strips	Not present	Not present	Not present	Not present	Not present
Number of lanes	Four or more	Four or more	Two	Two	Two
Lane width	Wide (>=3.25m)	Wide (>=3.25m)	Medium (>= 2.75m to <3.25m)	Medium (>= 2.75m to <3.25m)	Narrow (>= 0m to <2.75m)
Curvature	Straight or gently curving	Straight or gently curving	Straight or gently curving	Moderate	Moderate
Quality of curve	Adequate	Adequate	Adequate	Adequate	Poor
Grade	>= 0% to <7.5%	>= 0% to <7.5%	>= 0% to <7.5%	>= 0% to <7.5%	>= 7.5% to <10%
Road condition	Good	Good	Good	Good	Good
Skid resistance / grip	Sealed – adequate	Sealed – adequate	Sealed – adequate	Sealed – adequate	Sealed – adequate
Delineation	Adequate	Adequate	Adequate	Adequate	Adequate
Street lighting	Not present	Not present	Not present	Not present	Not present
Vehicle parking	None	None	None	None	None
Service road	Not present	Not present	Not present	Not present	Not present
Roadworks	No road works	No road works	No road works	No road works	No road works
Sight distance	Adequate	Adequate	Adequate	Poor	Poor
Vehicle flow (AADT)	40000	30000	20000	15000	7000
Land use - driver-side	Undeveloped areas	Undeveloped areas	Undeveloped areas	Undeveloped areas	Undeveloped areas
Land use - passenger-side	Undeveloped areas	Undeveloped areas	Undeveloped areas	Undeveloped areas	Undeveloped areas
Area type	Rural / open area	Urban/rural town	Urban/rural town	Rural / open area	Rural / open area
Speed limit	110km/h	90km/h	90km/h	80km/h	80km/h
Operating Speed (85th percentile)	95km/h	85km/h	85km/h	75km/h	75km/h

4.1 Basic Characteristics of the Homogeneous Road Section (With Junction)

Star Rating	★★★★★	★★★★	★★★	★★	
Star Rating Score	1.52	3.70	9.19	16.67	31.61
Intersection type					
• Merge lane	9.58	8.11	13.71	20.99	36.76
• Roundabout	21.05	14.40	20.00	27.27	44.30
• 3-leg protected signal	36.34	22.79	28.38	35.65	54.35
• 4-leg protected signal	44.41	27.21	32.81	40.07	59.66
Intersection channelisation	Present	Present	Present	Not Present	Not Present
Intersecting road volume	1000 to 5000	1000 to 5000	1000 to 5000	1000 to 5000	1000 to 5000
Intersection quality	Poor	Poor	Poor	Poor	Poor
Property access points	Commercial	Commercial	Commercial	Resident 1 or 2	Resident 1 or 2

4.2 Basic Characteristics of the Homogeneous Road Section

★★★★★	**Description:** Dual carriageway road with median barrier, roadside barrier, grade separated junctions and good delineation in a 90km/h speed zone **Location:** E8, 5.5 km from start of E8 (section 2, 0.896km)	
★★★★	**Description:** Dual carriageway road with median barrier, grade separated junctions and good delineation, 110 km/h speed zone **Location:** E1 exit 137 (section 16, 13.394 km)	
★★★	**Description:** Straight single carriageway road with relatively clear roadsides and some paved shoulders, 80km/h **Location:** F7, 11 km north of Kangar (F7, section 14, 0.298km)	
★★	**Description:** Single carriageway road with sharp curves, narrow paved shoulders and road side obstacles, 70km/h **Location:** F2, 26 km northeast of Maran (F2, section 19, 3.095km)	
★	**Description:** Single carriageway road, narrow paved shoulder, sharp curves, poor roadsides, 90 km/h **Location:** F1, 23.5 km southeast of Tanjong Malim (F1 section 97, 3.106 km)	

(Source: Adapted from iRAP, 2009)

Appendix 5 Star Rating Worked Example

iRAP Methodology Fact Sheet #9 : Star Rating Worked Example

This factsheet is part of a series that describes the iRAP methodology. It includes a worked example of the way in which Star Ratings are calculated.

5.1 Example Road

This worked example is based on the 100-metre segment of road shown in the image below.



5.2 Supporting Data

Attribute	Data / category
Vehicle flow (AADT)	15000
Motorcycle %	21% - 40%
Pedestrian peak hour flow across the road	26 to 50
Pedestrian peak hour flow along the road driver-side	101 to 200
Pedestrian peak hour flow along the road passenger-side	101 to 200
Bicycle peak hour flow	51 to 100
Speed - 85th percentile	50km/h

5.3 Vehicle occupant Star Rating Scores

a. Run-off road (driver side)

Type of risk factor	Category	Risk factor	Score
Road attribute (likelihood)			
Lane Width	Narrow (≥ 0m to <	1.10	
Curvature	Straight or gently curving	1.00	
Quality of curve	Not applicable	1.00	
Delineation	Poor	1.20	
Shoulder rumble strips	Not present	1.25	
Road condition	Good	1.00	
Grade	0% to < 7.5%	1.00	
Skid resistance / grip	Sealed - medium	1.40	
Product of road attribute (likelihood) risk factors			*2.310*
Road attribute (severity)			
Roadside severity - distance	≥ 10m	0.100	
Roadside severity - object	Tree ≥ 10cm	60.000	
Paved shoulder width	None	1.000	
Product of road attribute (severity) risk factors			*6.000*
External flow influence	15000 vehicles per day		*0.500*
Median traversability	Traversable		*1.000*
Operating speed	50km/h		*0.064*
Run-off road (driver side) Star Rating Score			**0.444**

b. Run-off road (passenger side)

Type of risk factor	Category	Risk factor	Score
Road attribute (likelihood)			
Lane Width	Narrow (≥ 0m to <	1.10	
Curvature	Straight or gently curving	1.00	
Quality of curve	Not applicable	1.00	
Delineation	Poor	1.20	
Shoulder rumble strips	Not present	1.25	
Road condition	Good	1.00	
Grade	0% to < 7.5%	1.00	
Skid resistance / grip	Sealed - medium	1.40	
Product of road attribute (likelihood) risk factors			*2.310*
Road attribute (severity)			
Roadside severity - distance	1 to <5m	0.80	
Roadside severity - object	Tree ≥ 10cm	60.00	
Paved shoulder width	None	1.00	
Product of road attribute (severity) risk factors			*48.000*
External flow influence	15000 vehicles per day		*0.500*
Operating speed	50km/h		*0.064*
Run-off road (driver side) Star Rating Score			**3.548**

c. Head-on (loss-of-control)

Type of risk factor	Category	Risk factor	Score
Road attribute (likelihood)			
Lane Width	Narrow (≥ 0m to <	1.10	
Curvature	Straight or gently curving	1.00	
Quality of curve	Not applicable	1.00	
Delineation	Poor	1.20	
Centreline rumble strips	Not present	1.20	
Road condition	Good	1.00	
Grade	0% to < 7.5%	1.00	
Skid resistance / grip	Sealed - medium	1.40	
Product of road attribute (likelihood) risk factors			*2.218*
Road attribute (severity)			
Median type	Physical median width ≥ 0m to < 1.0m	90.00	
Product of road attribute (severity) risk factors			*90.000*
External flow influence	15000 vehicles per day		*0.185*
Median traversability	Traversable		*1.000*
Operating speed	50km/h		*0.021*
Head-on (loss-of-control) Star Rating Score			**0.775**

d. Head-on (overtaking)

Type of risk factor	Category	Risk factor	Score
Road attribute (likelihood)			
Grade	0% to < 7.5%	1.00	
Skid resistance / grip	Sealed - medium	1.40	
Differential speeds	Present	1.20	
Number of lanes	Two	0.02	
Product of road attribute (likelihood) risk factors			*0.034*
Road attribute (severity)			
Median type	Physical median width ≥ 0m to < 1.0m	0.00	
Product of road attribute (severity) risk factors			*0.000*
External flow influence	15000 vehicles per day		*0.000*
Operating speed	50km/h		*0.021*
Head-on (overtaking) Star Rating Score			**0.000**

e. Intersection

Type of risk factor	Category	Risk factor	Score
Road attribute (likelihood)			
Intersection type	3-leg unsignalised with no protected	16.00	
Intersection quality	Poor	1.20	
Grade	0% to < 7.5%	1.00	
Street lighting	Not present	1.15	
Skid resistance / grip	Sealed - medium	1.40	
Sight distance	Adequate	1.00	
Intersection channelisation	Not present	1.20	
Speed management / traffic calming	Not present	1.25	
Product of road attribute (likelihood) risk factors			*46.368*
Road attribute (severity)			
Intersection type	3-leg unsignalised with no protected	45.00	
Product of road attribute (severity) risk factors			*45.000*
External flow influence	1,000 to 5,000 vehicles		*0.125*
Operating speed	50km/h		*0.064*
Intersection Star Rating Score			**16.692**

f. Property access

Type of risk factor	Category	Risk factor	Score
Road attribute (likelihood)			
Property access points	Commercial Access 1+	2.00	
Median type	Physical median width ≥ 0m to < 1.0m	0.70	
Service road	Not present	1.50	
Product of road attribute (likelihood) risk factors			*2.100*
Road attribute (severity)			
Property access points	Commercial Access 1+	50.00	
Product of road attribute (severity) risk factors			*50.000*
External flow influence	External flow influence - Default flow		*0.010*
Operating speed	50km/h		*0.064*
Intersection Star Rating Score			**0.067**

g. Vehicle occupant Star Rating Score and Star Rating

Crash type	Star Rating Score	Star Rating
Run-off road (driver side)	0.444	
Run-off road (passenger side)	3.548	
Head-on (loss-of-control)	0.775	
Head-on (overtaking)	0.000	
Intersection	16.692	
Property access	0.067	
Total Score / Star Rating	**21.527**	**2**

Appendix 6 Summary of Safer Road Treatment (iRAP Road Safety Toolkit)

Treatment	Costs	Treatment life	Effectiveness
1. Additional Lane	High	10 - 20 years	25-40%
2. Bicycle Facilities	Low to medium	10 - 20 years	25-40%
3. Central Hatching	Low	1 - 5 years	10-25%
4. Central Turning Lane Full Length	Low	1 - 5 years	10-25%
5. Delineation	Low	1 - 5 years	10-25%
6. Duplication	High	20 years +	25-40%
7. Intersection - Delineation	Low	1 - 5 years	10-25%
8. Intersection - Grade Separation	High	20 years +	25-40%
9. Intersection - Roundabout	Medium to high	10 - 20 years	60% or more
10. Intersection - Signalise	Medium	10 - 20 years	25-40%
11. Intersection - Turn Lanes (Signalised)	Low to medium	5 - 10 years	10-25%
12. Intersection - Turn Lanes (Unsignalised)	Low to medium	5 - 10 years	10-25%
13. Lane Widening	Medium to high	5 - 10 years	25-40%
14. Median Barrier	Medium to high	10 - 20 years	60% or more
15. Median Crossing Upgrade	Low to medium	5 - 10 years	25-40%
16. Motorcycle Lanes	Medium	10 - 20 years	25-40%
17. One Way Network	Medium	20 years +	25-40%
18. Parking Improvements	Low to medium	5 - 10 years	10-25%
19. Pedestrian Crossing - Grade Separation	High	20 years +	60% or more
20. Pedestrian Crossing - Signalised	Medium	10 - 20 years	25-40%
21. Pedestrian Crossing - Unsignalised	Low	1 - 5 years	25-40%
22. Pedestrian Fencing	Low	10 - 20 years	25-40%
23. Pedestrian Footpath	Low to medium	10 - 20 years	40-60%
24. Pedestrian Refuge Island	Low to medium	5 - 10 years	25-40%
25. Railway Crossing	Medium to high	10 - 20 years	60% or more
26. Realignment - Horizontal	High	20 years +	25-40%
27. Realignment - Vertical	High	20 years +	10-25%
28. Regulate Roadside Commercial Activity	Low to medium	1 - 5 years	10-25%
29. Restrict/Combine Direct Access Points	Medium	10 - 20 years	25-40%
30. Road Surface Rehabilitation	Medium	10 - 20 years	25-40%
31. Roadside Safety - Barriers	Medium	10 - 20 years	40-60%
32. Roadside Safety - Hazard Removal	Low to medium	5 - 10 years	25-40%
33. Rumble Strips	Low	1 - 5 years	10-25%
34. School Zones	Low to medium	5 - 10 years	10-25%
35. Service Road	High	20 years +	25-40%
36. Shoulder Sealing	Medium	5 - 10 years	25-40%
37. Sideslope Improvement	Medium	20 years +	10-25%

Appendix 6 Summary of Safer Road Treatment (iRAP Road Safety Toolkit) (cont'd)

Treatment	Costs	Treatment life	Effectiveness
38. Sight Distance (obstruction removal)	Low to medium	10 - 20 years	25-40%
39. Skid Resistance	Low to medium	5 - 10 years	25-40%
40. Speed Management	Medium	5 - 10 years	25-40%
41. Street Lighting	Medium	10 - 20 years	10-25%
42. Traffic Calming	Medium to high	10 - 20 years	25-40%

(Source: iRAP, 2019)

Appendix 7 Road Accident Statistics in Malaysia (1997-2015)

Year	Registered Vehicles	Road Crashes	Road Deaths	Serious Injury	Death per 100 mil' VKT	Serious per 100 mil' VKT
1997	8,550,469	215,632	6,302	14,105	335.7	751.4
1998	9,141,357	211,037	5,740	12,068	287.5	604.5
1999	9,929,951	223,166	5,794	10,366	267.9	479.3
2000	10,598,804	250,429	6,035	9,790	262.5	425.8
2001	11,302,545	265,175	5,849	8,680	239.3	355.1
2002	12,068,144	279,711	5,891	8,425	227.1	324.8
2003	12,819,248	298,653	6,286	9,040	227.7	327.5
2004	13,828,889	326,815	6,228	9,218	211.0	312.3
2005	15,026,660	328,264	6,200	9,395	195.8	296.7
2006	15,790,732	341,252	6,287	9,253	186.9	275.1
2007	16,813,943	363,319	6,282	9,273	176.0	259.8
2008	17,971,907	373,071	6,527	8,868	176.5	239.8
2009	19,016,782	397,330	6,745	8,849	172.7	226.6
2010	20,188,565	414,421	6,872	7,781	162.1	183.5
2011	21,401,269	449,040	6,877	6,328	146.8	135.1
2012	22,702,221	462,423	6,917	5,868	133.5	113.3
2013	23,819,256	477,204	6,915	4,597	121.9	81.0
2014	25,101,192	476,196	6,674	4,432	106.4	70.7
2015	26,301,952	489,606	6,706	4,120	96.0	59.0

Appendix 8 iRAP Recommended Countermeasure Programme

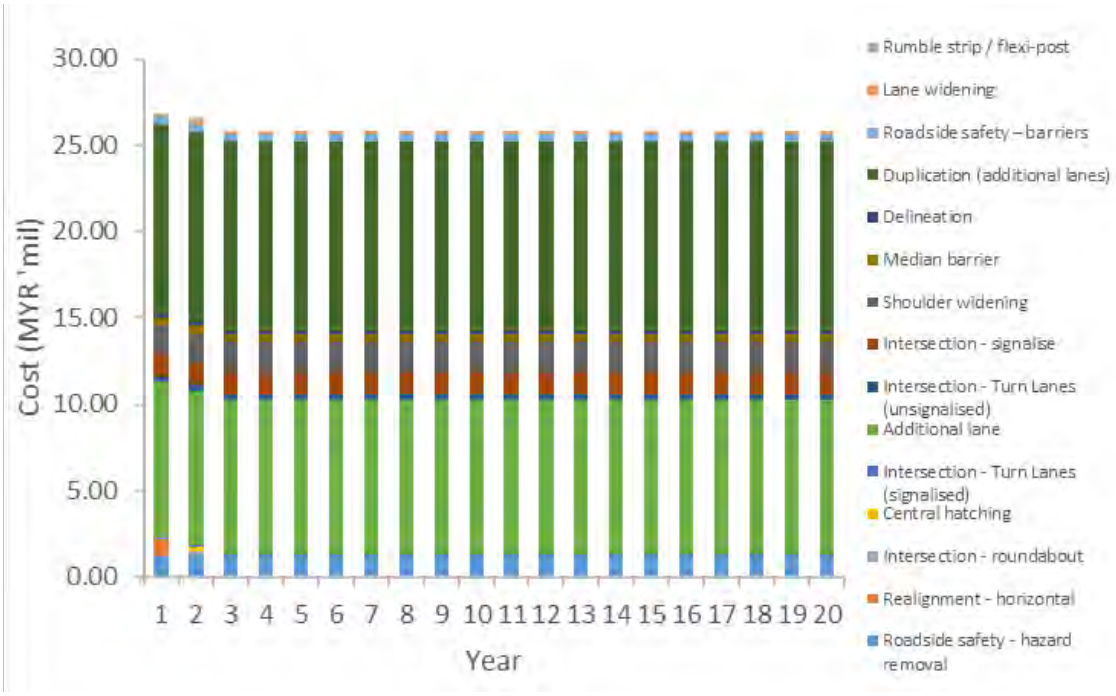
Countermeasure Type	Length or number of sites	Estimated Initial Construction Cost/ RM	Estimated Cost to Build and Maintain (20 years)/ RM	KSIs Saved (20 years)	Value of Safety Benefit (20 years)/ RM	Cost per KSI Saved (20 years)/ RM	Benefit-Cost Ratio
Roadside safety - hazard removal	1650 km	24 m	24 m	9,700	2,850 m	2,400	121
Additional lane	380 km	179 m	179 m	8,200	2,410 m	21,800	14
Duplication (additional lanes)	120 km	220 m	220 m	7,100	2,100 m	31,000	10
Shoulder widening	270 km	34 m	34 m	1,400	400 m	24,800	12
Intersection - signalise	190 sites	25 m	25 m	1,100	330 m	22,900	13
*Motorcycle lanes	270 km	15 m	17 m	900	260 m	19,200	15
Median barrier	40 km	10 m	20 m	800	240 m	25,300	12
Intersection - right turn provision (unsignalised site)	120 sites	7 m	14 m	600	180 m	21,800	14
Realignment - horizontal	3 km	1 m	1 m	500	150 m	2,500	117
Improve delineation	130 km	3 m	11 m	400	120 m	25,100	12
*Pedestrian crossing	130 sites	13 m	13 m	300	100 m	38,300	8
Roadside safety – barriers	30 km	9 m	9 m	300	80 m	30,100	10
Intersection - right turn provision (signalised site)	60 sites	2 m	4 m	200	70 m	18,100	16
Lane widening	30 km	3 m	6 m	200	50 m	33,100	9
Central hatching	10 km	0.2 m	0.4 m	40	10 m	8,200	36
Intersection - roundabout	20 sites	0.3 m	0.3 m	40	10 m	7,600	39
*Pedestrian footpath	10 km	2 m	2 m	40	10 m	40,000	7
*Road surface upgrade	10 km	0.4 m	0.8 m	30	10 m	26,600	11
Rumble strip / flexi-post	10 km	0.3 m	0.5 m	10	4 m	40,200	7
*Bicycle facilities on or off road	0.7 km	0.03 m	0.03 m	2	0.5 m	19,700	15
*Regulate roadside commercial activity	0.2 km	0.02 m	0.03 m	1	0.2 m	41,400	7
*Parking improvements	0.1 km	0.01 m	0.02 m	0	0.1 m	44,000	7
TOTAL		**556 m**	**578 m**	**31,800**	**9.3 bn**	**18,200**	**16**

(Source: iRAP, 2009)

Appendix 9 Annual Work Programme

9.1 Case I: Benefit-Cost Ratio Strategy

9.1.1 Road Safety Countermeasures Annual Distribution



9.1.2 Road Safety Countermeasures Priority

Countermeasure Type	CE Index	Length or number of sites	Unit	Construc-tion Cost (MYR)	Unit Cost (MYR)	Benefit-Cost Ratio
Roadside safety - hazard removal	C2	1650	km	24.00	0.01	121
Realignment - horizontal	C1	3	km	1.00	0.33	117
Intersection - roundabout	C2	20	sites	0.30	0.02	39
Central hatching	C5	10	km	0.20	0.02	36
Intersection - Turn Lanes (signalised)	C3	60	sites	2.00	0.03	16
Additional lane	C2	380	km	179.00	0.47	14
Intersection - Turn Lanes (unsignalised)	C3	120	sites	7.00	0.06	14
Intersection - signalise	C3	190	sites	25.00	0.13	13
Shoulder widening	C5	270	km	34.00	0.13	12
Median barrier	C2	40	km	10.00	0.25	12
Delineation	C5	130	km	3.00	0.02	12
Duplication (additional lanes)	C1	120	km	220.00	1.83	10
Roadside safety – barriers	C2	30	km	9.00	0.30	10
Lane widening	C2	30	km	3.00	0.10	9
Rumble strip / flexi-post	C5	10	km	0.30	0.03	7
TOTAL		**3063**		**517.80**	**25.89**	

9.1.3 Road Safety Countermeasures Work Programme

Countermeasure Type	CE Index	Year / Length (km)																				Total
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Roadside safety - hazard removal	C2	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	**1650**
Realignment - horizontal	C1	3																				**3**
Intersection - roundabout	C2		20																			**20**
Central hatching	C5		10	0																		**10**
Intersection - Turn Lanes (signalised)	C3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	**60**
Additional lane	C2	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	**380**
Intersection - Turn Lanes (unsignalised)	C3	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	**120**
Intersection - signalise	C3	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**190**
Shoulder widening	C5	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	**270**
Median barrier	C2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	**40**
Delineation	C5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	**130**
Duplication (additional lanes)	C1	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	**120**
Roadside safety – barriers	C2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	**30**
Lane widening	C2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	**30**
Rumble strip / flexi-post	C5		10																		0	**10**
TOTAL		**154**	**191**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**3063**

9.1.4 Road Management Assessment and Work Programme

9.1.4.1 Optimal +2

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	270.4	495.0	75.2	840.6	15,997	16,837	22	7,341	676	2,475	3,688	2.5	2.4
2	0.0	15.8	75.2	91.0	16,466	16,557	864	7,343	0	79	3,688	2.6	2.5
3	0.0	233.0	75.2	308.2	16,910	17,218	790	7,358	0	1,165	3,688	2.5	2.5
4	0.0	58.6	75.2	133.8	17,359	17,493	902	7,343	0	293	3,688	2.5	2.5
5	0.0	43.0	75.2	118.2	17,871	17,989	926	7,344	0	215	3,688	2.6	2.6
6	0.0	65.0	75.2	140.2	18,386	18,526	1,038	7,318	0	325	3,688	2.6	2.6
7	0.0	35.2	75.2	110.4	18,925	19,036	1,210	7,310	0	176	3,688	2.7	2.7
8	0.0	167.4	75.2	242.6	19,394	19,637	1,325	7,318	0	837	3,688	2.7	2.6
9	0.0	22.6	75.2	97.8	19,970	20,068	1,649	7,320	0	113	3,688	2.8	2.7
10	0.0	352.8	75.2	428.0	20,444	20,872	1,641	7,356	0	1,764	3,688	2.5	2.5
11	0.0	116.6	75.2	191.8	20,975	21,167	2,185	7,346	0	583	3,688	2.5	2.5
12	0.0	35.2	75.2	110.4	21,579	21,690	2,524	7,339	0	176	3,688	2.6	2.5
13	0.0	43.0	75.2	118.2	22,210	22,328	2,303	7,315	0	215	3,688	2.6	2.6
14	0.0	0.0	75.2	75.2	22,868	22,944	2,377	7,305	0	0	3,688	2.7	2.7
15	0.0	196.4	75.2	271.6	23,426	23,698	2,587	7,321	0	982	3,688	2.6	2.6
16	0.0	0.6	75.2	75.8	24,119	24,195	3,124	7,321	0	3	3,688	2.8	2.7
17	0.0	127.4	75.2	202.6	24,753	24,955	3,461	7,333	0	637	3,688	2.7	2.7
18	0.0	276.4	75.2	351.6	25,406	25,758	3,798	7,342	0	1,382	3,688	2.5	2.6
19	0.0	93.8	75.2	169.0	26,064	26,233	4,555	7,344	0	469	3,688	2.5	2.5
20	0.0	0.0	75.2	75.2	26,829	26,904	5,196	7,330	0	0	3,688	2.6	2.6
Years 1-5 Total	270.4	845.4	376.2	1,492.0	84,602	86,094	3,504	36,728	676	4,227	18,440		
Years 6-20 Total	0.0	1,532.4	1,128.5	2,660.9	335,348	338,009	38,973	109,918	0	7,662	55,320		
Years 1-20 Total	270.4	2,377.8	1,504.7	4,152.9	419,951	424,104	42,477	146,645	676	11,889	73,760		
Years 1-5 Total per Year	54.1	169.1	75.2	298.4	16,920	17,219	701	7,346	135	845	3,688		
Years 6-20 Total per Year	0.0	102.2	75.2	177.4	22,357	22,534	2,598	7,328	0	511	3,688		
Years 1-20 Total per Year	13.5	118.9	75.2	207.6	20,998	21,205	2,124	7,332	34	594	3,688		
PV at 12% (MYR 'mil)	270.4	1,202.9	629.4	2,102.7	159,464	161,567	11,691	61,365	676	6,015	30,853		
Rate of Return (%)							#NUM!						
Average (IRI)												2.6	2.6

* Comparison with Do Minimum Scenario

9.1.4.2 Optimal

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	270.4	452.0	68.0	790.4	16,006	16,796	63	7,302	676	2,260	3,688	2.6	2.5
2	0.0	0.0	68.0	68.0	16,478	16,546	875	7,302	0	0	3,688	2.7	2.6
3	0.0	233.0	68.0	301.0	16,924	17,225	783	7,303	0	1,165	3,688	2.6	2.5
4	0.0	101.6	68.0	169.6	17,361	17,531	865	7,328	0	508	3,688	2.5	2.5
5	0.0	15.8	68.0	83.8	17,874	17,957	958	7,339	0	79	3,688	2.6	2.6
6	0.0	65.0	68.0	133.0	18,389	18,522	1,041	7,313	0	325	3,688	2.7	2.6
7	0.0	0.0	68.0	68.0	18,940	19,008	1,238	7,307	0	0	3,688	2.8	2.8
8	0.0	202.6	68.0	270.6	19,398	19,669	1,293	7,279	0	1,013	3,688	2.7	2.6
9	0.0	22.0	68.0	90.0	19,974	20,064	1,653	7,281	0	110	3,688	2.8	2.7
10	0.0	332.4	68.0	400.4	20,454	20,855	1,658	7,349	0	1,662	3,688	2.6	2.6
11	0.0	117.2	68.0	185.2	20,988	21,173	2,179	7,331	0	586	3,688	2.6	2.5
12	0.0	13.0	68.0	81.0	21,603	21,684	2,530	7,305	0	65	3,688	2.6	2.6
13	0.0	34.6	68.0	102.6	22,224	22,327	2,305	7,293	0	173	3,688	2.7	2.7
14	0.0	15.8	68.0	83.8	22,883	22,966	2,354	7,269	0	79	3,688	2.8	2.8
15	0.0	231.6	68.0	299.6	23,425	23,724	2,560	7,321	0	1,158	3,688	2.7	2.6
16	0.0	0.0	68.0	68.0	24,117	24,185	3,134	7,321	0	0	3,688	2.8	2.7
17	0.0	114.4	68.0	182.4	24,751	24,934	3,482	7,332	0	572	3,688	2.8	2.6
18	0.0	226.0	68.0	294.0	25,419	25,713	3,843	7,297	0	1,130	3,688	2.6	2.6
19	0.0	58.6	68.0	126.6	26,092	26,219	4,569	7,296	0	293	3,688	2.7	2.6
20	0.0	43.6	68.0	111.6	26,852	26,964	5,136	7,318	0	218	3,688	2.7	2.7
Years 1-5 Total	270.4	802.4	339.9	1,412.7	84,643	86,055	3,543	36,576	676	4,012	18,440		
Years 6-20 Total	0.0	1,476.8	1,019.7	2,496.5	335,509	338,006	38,976	109,611	0	7,384	55,320		
Years 1-20 Total	270.4	2,279.2	1,359.7	3,909.3	420,152	424,061	42,519	146,187	676	11,396	73,760		
Years 1-5 Total per Year	54.1	160.5	68.0	282.5	16,929	17,211	709	7,315	135	802	3,688		
Years 6-20 Total per Year	0.0	98.5	68.0	166.4	22,367	22,534	2,598	7,307	0	492	3,688		
Years 1-20 Total per Year	13.5	114.0	68.0	195.5	21,008	21,203	2,126	7,309	34	570	3,688		
PV at 12% (MYR 'mil)	270.4	1,143.0	568.7	1,982.1	159,540	161,523	11,735	61,151	676	5,715	30,853		
Rate of Return (%)							#NUM!						
Average (IRI)												2.6	2.6

* Comparison with Do Minimum Scenario

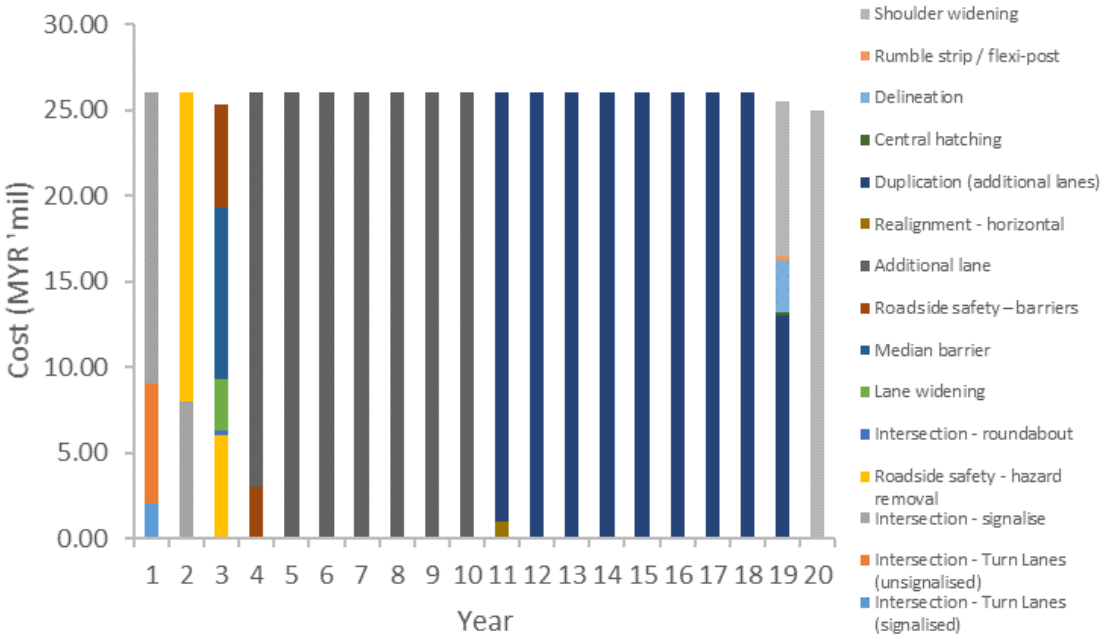
9.1.4.3 Optimal -2

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	2.0	0.0	64.4	66.4	16,827	16,893	-34	6,804	5	0	3,688	4.9	4.2
2	0.0	0.0	64.4	64.4	17,388	17,452	-32	6,804	0	0	3,688	5.2	4.4
3	172.0	284.6	64.4	521.0	17,343	17,864	145	7,175	430	1,423	3,688	3.7	3.3
4	96.4	168.4	64.4	329.2	17,435	17,764	631	7,266	241	842	3,688	2.8	2.7
5	0.0	0.0	64.4	64.4	17,956	18,021	894	7,245	0	0	3,688	3.0	2.8
6	0.0	6.0	64.4	70.4	18,490	18,561	1,003	7,234	0	30	3,688	3.1	2.9
7	0.0	0.0	64.4	64.4	19,052	19,116	1,129	7,230	0	0	3,688	3.3	3.0
8	0.0	285.6	64.4	350.0	19,480	19,829	1,133	7,257	0	1,428	3,688	3.0	2.8
9	0.0	58.0	64.4	122.4	20,052	20,174	1,543	7,232	0	290	3,688	3.1	2.9
10	0.0	6.0	64.4	70.4	20,652	20,722	1,790	7,194	0	30	3,688	3.2	3.0
11	0.0	0.0	64.4	64.4	21,286	21,350	2,002	7,186	0	0	3,688	3.4	3.1
12	0.0	0.0	64.4	64.4	21,947	22,011	2,202	7,155	0	0	3,688	3.6	3.3
13	0.0	246.8	64.4	311.2	22,362	22,673	1,959	7,175	0	1,234	3,688	3.4	2.9
14	0.0	0.0	64.4	64.4	23,045	23,109	2,211	7,144	0	0	3,688	3.5	3.0
15	0.0	64.0	64.4	128.4	23,722	23,851	2,434	7,133	0	320	3,688	3.6	3.1
16	0.0	0.0	64.4	64.4	24,459	24,523	2,795	7,105	0	0	3,688	3.8	3.2
17	0.0	226.0	64.4	290.4	25,131	25,422	2,994	7,127	0	1,130	3,688	3.7	3.2
18	0.0	58.6	64.4	123.0	25,807	25,930	3,626	7,110	0	293	3,688	3.8	3.1
19	0.0	1.0	64.4	65.4	26,615	26,680	4,108	7,087	0	5	3,688	4.0	3.3
20	0.0	0.0	64.4	64.4	27,460	27,525	4,575	7,087	0	0	3,688	4.2	3.4
Years 1-5 Total	270.4	453.0	321.8	1,045.2	86,949	87,994	1,605	35,295	676	2,265	18,440		
Years 6-20 Total	0.0	952.0	965.4	1,917.4	339,560	341,478	35,504	107,456	0	4,760	55,320		
Years 1-20 Total	270.4	1,405.0	1,287.1	2,962.5	426,509	429,472	37,109	142,751	676	7,025	73,760		
Years 1-5 Total per Year	54.1	90.6	64.4	209.0	17,390	17,599	321	7,059	135	453	3,688		
Years 6-20 Total per Year	0.0	63.5	64.4	127.8	22,637	22,765	2,367	7,164	0	317	3,688		
Years 1-20 Total per Year	13.5	70.3	64.4	148.1	21,325	21,474	1,855	7,138	34	351	3,688		
PV at 12% (MYR 'mil)	207.7	626.9	538.4	1,373.0	162,514	163,887	9,371	59,491	519	3,135	30,853		
Rate of Return (%)							226%						
Average (IRI)												3.6	3.2

* Comparison with Do Minimum Scenario

9.2 *Case II: Treatment-Based Strategy*

9.2.1 *Road Safety Countermeasures Annual Distribution*



9.2.2 *Road Safety Countermeasures Priority*

Countermeasure Type	CE Index	Length or number of sites	Unit	Construction Cost (MYR)	Unit Cost (MYR)	Benefit-Cost Ratio
Intersection - Turn Lanes (signalised)	C3	60	sites	2.00	0.03	16
Intersection - Turn Lanes (unsignalised)	C3	120	sites	7.00	0.06	14
Intersection - signalise	C3	190	sites	25.00	0.13	13
Roadside safety - hazard removal	C2	1650	km	24.00	0.01	121
Intersection - roundabout	C2	20	sites	0.30	0.02	39
Lane widening	C2	30	km	3.00	0.10	9
Median barrier	C2	40	km	10.00	0.25	12
Roadside safety – barriers	C2	30	km	9.00	0.30	10
Additional lane	C2	380	km	179.00	0.47	14
Realignment - horizontal	C1	3	km	1.00	0.33	117
Duplication (additional lanes)	C1	120	km	220.00	1.83	10
Central hatching	C5	10	km	0.20	0.02	36
Delineation	C5	130	km	3.00	0.02	12
Rumble strip / flexi-post	C5	10	km	0.30	0.03	7
Shoulder widening	C5	270	km	34.00	0.13	12
TOTAL		**3063**		**517.80**	**25.89**	

9.2.3 Road Safety Countermeasures Work Programme

Countermeasure Type	CE Index	Length																				Total
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Intersection - Turn Lanes (signalised)	C3	60																				**60**
Intersection - Turn Lanes (unsignalised)	C3	120																				**120**
Intersection - signalise	C3	129	61																			**190**
Roadside safety - hazard removal	C2		1238	413																		**1650**
Intersection - roundabout	C2			20																		**20**
Lane widening	C2			30																		**30**
Median barrier	C2			40																		**40**
Roadside safety – barriers	C2			20	10																	**30**
Additional lane	C2				49	55	55	55	55	55	55											**380**
Realignment - horizontal	C1											3										**3**
Duplication (additional lanes)	C1											14	14	14	14	14	14	14	14	7		**120**
Central hatching	C5																			10		**10**
Delineation	C5																			130		**130**
Rumble strip / flexi-post	C5																			10		**10**
Shoulder widening	C5																			71	199	**270**
TOTAL		**309**	**1298**	**523**	**59**	**55**	**55**	**55**	**55**	**55**	**55**	**17**	**14**	**14**	**14**	**14**	**14**	**14**	**14**	**229**	**199**	**3063**

9.2.4 Road Management Assessment and Work Programme

9.2.4.1 Custom +2

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	194 4	320 8	75 2	590 4	16,337	16,927	-68	7,220	486	1,604	3,688	3 1	3 3
2	64 0	40 2	75 2	179 4	16,730	16,910	511	7,272	160	201	3,688	2 9	3 2
3	12 0	200 6	75 2	287 8	17,015	17,303	706	7,342	30	1,003	3,688	2 6	2 8
4	0 0	92 2	75 2	167 4	17,412	17,580	816	7,341	0	461	3,688	2 6	2 6
5	0 0	0 0	75 2	75 2	17,932	18,007	908	7,325	0	0	3,688	2 7	2 7
6	0 0	176 2	75 2	251 4	18,420	18,671	892	7,318	0	881	3,688	2 7	2 7
7	0 0	34 4	75 2	109 6	18,965	19,075	1,171	7,322	0	172	3,688	2 7	2 8
8	0 0	127 6	75 2	202 8	19,439	19,642	1,320	7,315	0	638	3,688	2 7	2 7
9	0 0	50 0	75 2	125 2	20,015	20,141	1,577	7,311	0	250	3,688	2 8	2 8
10	0 0	207 8	75 2	283 0	20,569	20,852	1,661	7,330	0	1,039	3,688	2 7	2 8
11	0 0	43 2	75 2	118 4	21,177	21,295	2,057	7,326	0	216	3,688	2 7	2 9
12	0 0	18 0	75 2	93 2	21,813	21,906	2,308	7,321	0	90	3,688	2 8	3 0
13	0 0	180 6	75 2	255 8	22,228	22,484	2,147	7,315	0	903	3,688	2 7	2 7
14	0 0	143 4	75 2	218 6	22,845	23,064	2,256	7,319	0	717	3,688	2 7	2 7
15	0 0	77 0	75 2	152 2	23,500	23,652	2,633	7,323	0	385	3,688	2 7	2 7
16	0 0	15 0	75 2	90 2	24,195	24,285	3,034	7,311	0	75	3,688	2 8	2 8
17	0 0	86 2	75 2	161 4	24,903	25,065	3,351	7,318	0	431	3,688	2 8	2 9
18	0 0	217 4	75 2	292 6	25,491	25,784	3,772	7,333	0	1,087	3,688	2 6	2 7
19	0 0	19 0	75 2	94 2	26,240	26,335	4,454	7,323	0	95	3,688	2 7	2 8
20	0 0	32 0	75 2	107 2	27,012	27,120	4,980	7,314	0	160	3,688	2 8	2 9
Years 1-5 Total	270 4	653 8	376 2	1,300 4	85,426	86,727	2,872	36,499	676	3,269	18,440		
Years 6-20 Total	0 0	1,427 8	1,128 5	2,556 3	336,813	339,369	37,613	109,801	0	7,139	55,320		
Years 1-20 Total	270 4	2,081 6	1,504 7	3,856 7	422,239	426,096	40,485	146,300	676	10,408	73,760		
Years 1-5 Total per Year	54 1	130 8	75 2	260 1	17,085	17,345	574	7,300	135	654	3,688		
Years 6-20 Total per Year	0 0	95 2	75 2	170 4	22,454	22,625	2,508	7,320	0	476	3,688		
Years 1-20 Total per Year	13 5	104 1	75 2	192 8	21,112	21,305	2,024	7,315	34	520	3,688		
PV at 12% (MYR 'mil)	261 1	1,021 2	629 4	1,911 7	160,566	162,477	10,781	61,128	653	5,106	30,853		
Rate of Return (%)							783%						
Average (IRI)												2 7	2 8

* Comparison with Do Minimum Scenario

9.2.4.2 Custom

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	108 4	50 8	52 3	211 5	16,575	16,786	73	6,952	271	254	3,688	4 1	3 8
2	42 0	16 8	52 3	111 1	17,078	17,189	231	6,986	105	84	3,688	4 0	3 9
3	44 0	106 0	52 3	202 3	17,477	17,679	330	7,103	110	530	3,688	3 7	3 8
4	64 0	33 2	52 3	149 5	17,902	18,052	344	7,030	160	166	3,688	3 5	3 7
5	0 0	197 2	52 3	249 5	18,313	18,562	353	7,147	0	986	3,688	3 2	3 6
6	0 0	6 0	52 3	58 3	18,886	18,945	619	7,136	0	30	3,688	3 3	3 8
7	0 0	3 8	52 3	56 1	19,486	19,542	703	7,125	0	19	3,688	3 5	3 9
8	0 0	130 2	52 3	182 5	20,066	20,248	714	7,134	0	651	3,688	3 4	4 0
9	0 0	29 6	52 3	81 9	20,704	20,786	931	7,013	0	148	3,688	3 6	4 2
10	12 0	41 6	52 3	105 9	21,275	21,380	1,132	6,998	30	208	3,688	3 6	4 2
11	0 0	176 0	52 3	228 3	21,894	22,122	1,230	7,139	0	880	3,688	3 5	4 2
12	0 0	16 2	52 3	68 5	22,605	22,674	1,540	7,119	0	81	3,688	3 6	4 4
13	0 0	86 8	52 3	139 1	23,327	23,466	1,166	7,004	0	434	3,688	3 7	4 6
14	2 0	23 0	52 3	77 3	24,079	24,157	1,164	6,989	5	115	3,688	3 8	4 8
15	0 0	87 2	52 3	139 5	24,852	24,991	1,293	7,036	0	436	3,688	3 9	5 0
16	0 0	0 6	52 3	52 9	25,696	25,749	1,570	7,033	0	3	3,688	4 1	5 2
17	0 0	117 0	52 3	169 3	26,538	26,708	1,708	7,015	0	585	3,688	4 1	5 4
18	0 0	66 6	52 3	118 9	27,434	27,553	2,003	7,037	0	333	3,688	4 2	5 6
19	0 0	2 0	52 3	54 3	28,394	28,448	2,340	7,007	0	10	3,688	4 4	5 9
20	0 0	4 0	52 3	56 3	29,399	29,455	2,644	6,885	0	20	3,688	4 6	6 2
Years 1-5 Total	258 4	404 0	261 4	923 8	87,344	88,268	1,330	35,218	646	2,020	18,440		
Years 6-20 Total	14 0	790 6	784 3	1,588 9	354,635	356,224	20,758	105,673	35	3,953	55,320		
Years 1-20 Total	272 4	1,194 6	1,045 7	2,512 7	441,980	444,492	22,088	140,891	681	5,973	73,760		
Years 1-5 Total per Year	51 7	80 8	52 3	184 8	17,469	17,654	266	7,044	129	404	3,688		
Years 6-20 Total per Year	0 9	52 7	52 3	105 9	23,642	23,748	1,384	7,045	2	264	3,688		
Years 1-20 Total per Year	13 6	59 7	52 3	125 6	22,099	22,225	1,104	7,045	34	299	3,688		
PV at 12% (MYR 'mil)	231 3	526 8	437 4	1,195 5	166,099	167,294	5,964	58,990	578	2,634	30,853		
Rate of Return (%)							#NUM!						
Average (IRI)												3 8	4 5

* Comparison with Do Minimum Scenario

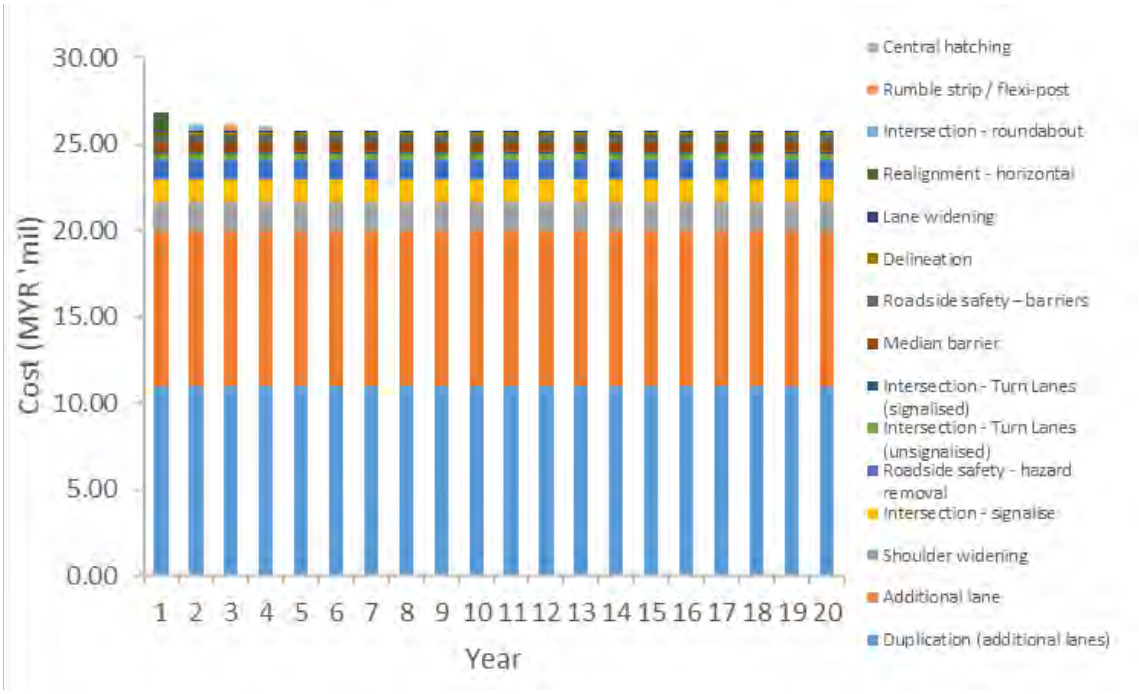
9.2.4.3 Custom -2

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	60 4	0 0	27 3	87 7	16,713	16,801	58	6,863	151	0	3,688	4 5	4 1
2	0 0	13 0	27 3	40 3	17,259	17,299	121	6,874	0	65	3,688	4 7	4 2
3	10 0	1 8	27 3	39 1	17,827	17,866	142	6,869	25	9	3,688	4 9	4 4
4	80 0	30 0	27 3	137 3	18,221	18,358	37	6,814	200	150	3,688	4 5	4 3
5	0 0	22 8	27 3	50 1	18,822	18,872	43	6,691	0	114	3,688	4 6	4 5
6	0 0	0 0	27 3	27 3	19,462	19,489	74	6,684	0	0	3,688	4 9	4 7
7	0 0	13 0	27 3	40 3	20,132	20,172	73	6,652	0	65	3,688	5 1	5 0
8	0 0	2 0	27 3	29 3	20,837	20,866	96	6,610	0	10	3,688	5 3	5 2
9	0 0	0 0	27 3	27 3	21,580	21,607	110	6,603	0	0	3,688	5 6	5 5
10	44 0	30 0	27 3	101 3	22,192	22,294	219	6,653	110	150	3,688	5 5	5 5
11	0 0	12 6	27 3	39 9	22,994	23,034	318	6,653	0	63	3,688	5 8	5 8
12	0 0	12 8	27 3	40 1	23,843	23,883	331	6,631	0	64	3,688	6 1	6 1
13	64 0	5 8	27 3	97 1	24,417	24,514	117	6,539	160	29	3,688	5 9	6 1
14	12 0	14 0	27 3	53 3	25,198	25,251	70	6,546	30	70	3,688	6 1	6 2
15	0 0	21 8	27 3	49 1	26,156	26,205	79	6,552	0	109	3,688	6 4	6 5
16	0 0	13 0	27 3	40 3	27,175	27,215	104	6,533	0	65	3,688	6 7	6 9
17	0 0	0 0	27 3	27 3	28,256	28,283	133	6,523	0	0	3,688	7 1	7 3
18	2 0	4 0	27 3	33 3	29,374	29,407	149	6,392	5	20	3,688	7 4	7 6
19	0 0	2 0	27 3	29 3	30,588	30,617	171	6,313	0	10	3,688	7 8	8 0
20	0 0	30 6	27 3	57 9	31,871	31,929	171	6,325	0	153	3,688	8 2	8 5
Years 1-5 Total	150 4	67 6	136 3	354 3	88,843	89,197	402	34,111	376	338	18,440		
Years 6-20 Total	122 0	161 6	408 8	692 4	374,076	374,768	2,214	98,208	305	808	55,320		
Years 1-20 Total	272 4	229 2	545 1	1,046 7	462,918	463,965	2,616	132,320	681	1,146	73,760		
Years 1-5 Total per Year	30 1	13 5	27 3	70 9	17,769	17,839	80	6,822	75	68	3,688		
Years 6-20 Total per Year	8 1	10 8	27 3	46 2	24,938	24,985	148	6,547	20	54	3,688		
Years 1-20 Total per Year	13 6	11 5	27 3	52 3	23,146	23,198	131	6,616	34	57	3,688		
PV at 12% (MYR 'mil)	160 6	90 9	228 0	479 5	171,835	172,314	944	56,109	402	454	30,853		
Rate of Return (%)							#NUM!						
Average (IRI)												5 9	5 8

* Comparison with Do Minimum Scenario

9.3 Case III: Average Budget Strategy

9.3.1 Road Safety Countermeasures Annual Distribution



9.3.2 Road Safety Countermeasures Priority

Countermeasure Type	CE Index	Length or number of sites	Unit	Construction Cost (MYR)	Unit Cost (MYR)	Benefit-Cost Ratio
Duplication (additional lanes)	C1	120	km	220.00	1.83	10
Additional lane	C2	380	km	179.00	0.47	14
Shoulder widening	C5	270	km	34.00	0.13	12
Intersection - signalise	C3	190	sites	25.00	0.13	13
Roadside safety - hazard removal	C2	1650	km	24.00	0.01	121
Intersection - Turn Lanes (unsignalised)	C3	120	sites	7.00	0.06	14
Intersection - Turn Lanes (signalised)	C3	60	sites	2.00	0.03	16
Median barrier	C2	40	km	10.00	0.25	12
Roadside safety – barriers	C2	30	km	9.00	0.30	10
Delineation	C5	130	km	3.00	0.02	12
Lane widening	C2	30	km	3.00	0.10	9
Realignment - horizontal	C1	3	km	1.00	0.33	117
Intersection - roundabout	C2	20	sites	0.30	0.02	39
Rumble strip / flexi-post	C5	10	km	0.30	0.03	7
Central hatching	C5	10	km	0.20	0.02	36
TOTAL		**3063**		**517.80**	**25.89**	

9.3.3 Road Safety Countermeasures Work Programme

Countermeasure Type	CE Index	Length																				Total
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
Duplication (additional lanes)	C1	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	**120**
Additional lane	C2	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	19	**380**
Shoulder widening	C5	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	14	**270**
Intersection - signalise	C3	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	10	**190**
Roadside safety - hazard removal	C2	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	83	**1650**
Intersection - Turn Lanes (unsignalised)	C3	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	6	**120**
Intersection - Turn Lanes (signalised)	C3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	**60**
Median barrier	C2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	**40**
Roadside safety – barriers	C2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	**30**
Delineation	C5	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	7	**130**
Lane widening	C2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	**30**
Realignment - horizontal	C1																				3	**3**
Intersection - roundabout	C2																				20	**20**
Rumble strip / flexi-post	C5																				10	**10**
Central hatching	C5																				10	**10**
TOTAL		**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**151**	**194**	**3063**

9.3.4 Road Management Assessment and Work Programme

9.3.4.1 Very High

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	270 4	510 8	75 2	856 4	15,995	16,852	7	7,343	676	2,554	3,688	2 5	2 4
2	0 0	0 0	75 2	75 2	16,466	16,541	879	7,343	0	0	3,688	2 6	2 5
3	0 0	276 0	75 2	351 2	16,908	17,259	750	7,361	0	1,380	3,688	2 4	2 5
4	0 0	58 6	75 2	133 8	17,357	17,490	905	7,347	0	293	3,688	2 5	2 5
5	0 0	0 0	75 2	75 2	17,871	17,946	969	7,344	0	0	3,688	2 6	2 6
6	0 0	100 2	75 2	175 4	18,378	18,554	1,010	7,317	0	501	3,688	2 6	2 6
7	0 0	16 4	75 2	91 6	18,925	19,017	1,229	7,312	0	82	3,688	2 7	2 7
8	0 0	167 4	75 2	242 6	19,394	19,637	1,325	7,320	0	837	3,688	2 7	2 6
9	0 0	69 6	75 2	144 8	19,961	20,106	1,611	7,327	0	348	3,688	2 7	2 7
10	0 0	332 4	75 2	407 6	20,443	20,850	1,662	7,359	0	1,662	3,688	2 5	2 5
11	0 0	151 8	75 2	227 0	20,965	21,192	2,160	7,350	0	759	3,688	2 4	2 4
12	0 0	0 0	75 2	75 2	21,578	21,653	2,561	7,344	0	0	3,688	2 5	2 5
13	0 0	0 0	75 2	75 2	22,213	22,288	2,344	7,307	0	0	3,688	2 6	2 6
14	0 0	16 4	75 2	91 6	22,870	22,962	2,359	7,302	0	82	3,688	2 7	2 7
15	0 0	209 4	75 2	284 6	23,427	23,712	2,573	7,324	0	1,047	3,688	2 6	2 6
16	0 0	34 6	75 2	109 8	24,111	24,221	3,098	7,327	0	173	3,688	2 7	2 7
17	0 0	192 6	75 2	267 8	24,731	24,998	3,417	7,345	0	963	3,688	2 6	2 6
18	0 0	226 0	75 2	301 2	25,395	25,696	3,860	7,347	0	1,130	3,688	2 5	2 5
19	0 0	58 6	75 2	133 8	26,065	26,198	4,590	7,340	0	293	3,688	2 5	2 5
20	0 0	0 0	75 2	75 2	26,830	26,905	5,195	7,330	0	0	3,688	2 6	2 6
Years 1-5 Total	270 4	845 4	376 2	1,492 0	84,596	86,088	3,510	36,736	676	4,227	18,440		
Years 6-20 Total	0 0	1,575 4	1,128 5	2,703 9	335,285	337,989	38,993	109,949	0	7,877	55,320		
Years 1-20 Total	270 4	2,420 8	1,504 7	4,195 9	419,881	424,077	42,503	146,686	676	12,104	73,760		
Years 1-5 Total per Year	54 1	169 1	75 2	298 4	16,919	17,218	702	7,347	135	845	3,688		
Years 6-20 Total per Year	0 0	105 0	75 2	180 3	22,352	22,533	2,600	7,330	0	525	3,688		
Years 1-20 Total per Year	13 5	121 0	75 2	209 8	20,994	21,204	2,125	7,334	34	605	3,688		
PV at 12% (MYR 'mil)	270 4	1,235 2	629 4	2,135 0	159,442	161,577	11,681	61,380	676	6,176	30,853		
Rate of Return (%)							#NUM!						
Average (IRI)												2 6	2 6

* Comparison with Do Minimum Scenario

9.3.4.2 Medium

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	98 4	0 0	75 2	173 6	16,592	16,766	93	6,901	246	0	3,688	4 2	3 9
2	0 0	43 0	75 2	118 2	17,120	17,238	182	6,939	0	215	3,688	4 3	4 0
3	172 0	300 4	75 2	547 6	17,047	17,595	414	7,325	430	1,502	3,688	2 8	2 9
4	0 0	168 4	75 2	243 6	17,423	17,667	729	7,337	0	842	3,688	2 7	2 7
5	0 0	0 0	75 2	75 2	17,943	18,018	897	7,316	0	0	3,688	2 8	2 8
6	0 0	6 0	75 2	81 2	18,476	18,557	1,007	7,303	0	30	3,688	2 9	2 9
7	0 0	43 0	75 2	118 2	19,031	19,149	1,096	7,307	0	215	3,688	3 0	3 0
8	0 0	320 8	75 2	396 0	19,441	19,837	1,125	7,330	0	1,604	3,688	2 7	2 7
9	0 0	58 0	75 2	133 2	20,006	20,140	1,578	7,307	0	290	3,688	2 7	2 8
10	0 0	6 6	75 2	81 8	20,598	20,680	1,833	7,301	0	33	3,688	2 9	2 9
11	0 0	13 0	75 2	88 2	21,221	21,309	2,043	7,302	0	65	3,688	3 0	3 0
12	0 0	50 4	75 2	125 6	21,852	21,978	2,236	7,302	0	252	3,688	3 0	3 1
13	0 0	246 8	75 2	322 0	22,250	22,572	2,060	7,320	0	1,234	3,688	2 8	2 7
14	0 0	35 2	75 2	110 4	22,898	23,009	2,312	7,304	0	176	3,688	2 9	2 8
15	0 0	64 0	75 2	139 2	23,550	23,689	2,596	7,307	0	320	3,688	2 9	2 8
16	0 0	43 0	75 2	118 2	24,250	24,368	2,951	7,305	0	215	3,688	3 0	3 0
17	0 0	226 0	75 2	301 2	24,886	25,187	3,229	7,324	0	1,130	3,688	2 8	2 9
18	0 0	59 2	75 2	134 4	25,521	25,655	3,901	7,307	0	296	3,688	2 8	2 8
19	0 0	14 0	75 2	89 2	26,279	26,368	4,420	7,302	0	70	3,688	2 9	2 9
20	0 0	0 0	75 2	75 2	27,071	27,146	4,954	7,301	0	0	3,688	3 0	3 0
Years 1-5 Total	270 4	511 8	376 2	1,158 4	86,126	87,285	2,314	35,818	676	2,559	18,440		
Years 6-20 Total	0 0	1,186 0	1,128 5	2,314 5	337,329	339,644	37,338	109,623	0	5,930	55,320		
Years 1-20 Total	270 4	1,697 8	1,504 7	3,472 9	423,455	426,928	39,652	145,441	676	8,489	73,760		
Years 1-5 Total per Year	54 1	102 4	75 2	231 7	17,225	17,457	463	7,164	135	512	3,688		
Years 6-20 Total per Year	0 0	79 1	75 2	154 3	22,489	22,643	2,489	7,308	0	395	3,688		
Years 1-20 Total per Year	13 5	84 9	75 2	173 6	21,173	21,346	1,983	7,272	34	424	3,688		
PV at 12% (MYR 'mil)	235 5	752 2	629 4	1,617 1	161,359	162,977	10,281	60,443	589	3,761	30,853		
Rate of Return (%)							#NUM!						
Average (IRI)												3 0	3 0

* Comparison with Do Minimum Scenario

9.3.4.3 Very Low

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	98 4	0 0	37 6	136 0	16,592	16,728	130	6,901	246	0	3,688	4 2	3 9
2	0 0	0 0	37 6	37 6	17,131	17,169	252	6,901	0	0	3,688	4 4	4 0
3	0 0	0 0	37 6	37 6	17,694	17,732	277	6,886	0	0	3,688	4 7	4 2
4	0 0	0 0	37 6	37 6	18,285	18,323	73	6,710	0	0	3,688	4 9	4 4
5	0 0	0 0	37 6	37 6	18,904	18,942	-27	6,564	0	0	3,688	5 1	4 7
6	0 0	0 0	37 6	37 6	19,555	19,592	-29	6,546	0	0	3,688	5 4	4 9
7	0 0	0 0	37 6	37 6	20,238	20,276	-31	6,514	0	0	3,688	5 7	5 1
8	0 0	0 0	37 6	37 6	20,958	20,995	-33	6,482	0	0	3,688	6 0	5 4
9	44 0	0 0	37 6	81 6	21,665	21,747	-29	6,526	110	0	3,688	6 0	5 6
10	128 0	0 0	37 6	165 6	21,928	22,093	420	6,653	320	0	3,688	5 4	5 2
11	0 0	0 0	37 6	37 6	22,718	22,756	597	6,633	0	0	3,688	5 7	5 5
12	0 0	0 0	37 6	37 6	23,553	23,590	623	6,602	0	0	3,688	6 0	5 8
13	0 0	0 0	37 6	37 6	24,435	24,473	159	6,436	0	0	3,688	6 3	6 1
14	2 0	0 0	37 6	39 6	25,350	25,389	-69	6,438	5	0	3,688	6 7	6 4
15	0 0	0 0	37 6	37 6	26,337	26,375	-91	6,435	0	0	3,688	7 1	6 8
16	0 0	0 0	37 6	37 6	27,385	27,423	-104	6,362	0	0	3,688	7 5	7 1
17	0 0	0 0	37 6	37 6	28,497	28,535	-119	6,360	0	0	3,688	7 9	7 5
18	86 0	0 0	37 6	123 6	29,559	29,682	-126	6,327	215	0	3,688	7 8	7 8
19	0 0	0 0	37 6	37 6	30,801	30,838	-50	6,260	0	0	3,688	8 2	8 3
20	0 0	0 0	37 6	37 6	32,121	32,158	-59	6,257	0	0	3,688	8 7	8 7
Years 1-5 Total	98 4	0 0	188 1	286 5	88,607	88,894	705	33,962	246	0	18,440		
Years 6-20 Total	260 0	0 0	564 3	824 3	375,098	375,923	1,059	96,832	650	0	55,320		
Years 1-20 Total	358 4	0 0	752 4	1,110 8	463,706	464,816	1,764	130,794	896	0	73,760		
Years 1-5 Total per Year	19 7	0 0	37 6	57 3	17,721	17,779	141	6,792	49	0	3,688		
Years 6-20 Total per Year	17 3	0 0	37 6	55 0	25,007	25,062	71	6,455	43	0	3,688		
Years 1-20 Total per Year	17 9	0 0	37 6	55 5	23,185	23,241	88	6,540	45	0	3,688		
PV at 12% (MYR 'mil)	175 3	0 0	314 7	490 0	171,757	172,247	1,011	55,621	438	0	30,853		
Rate of Return (%)							#NUM!						
Average (IRI)												6 2	5 9

* Comparison with Do Minimum Scenario

9.4 Base Scenario

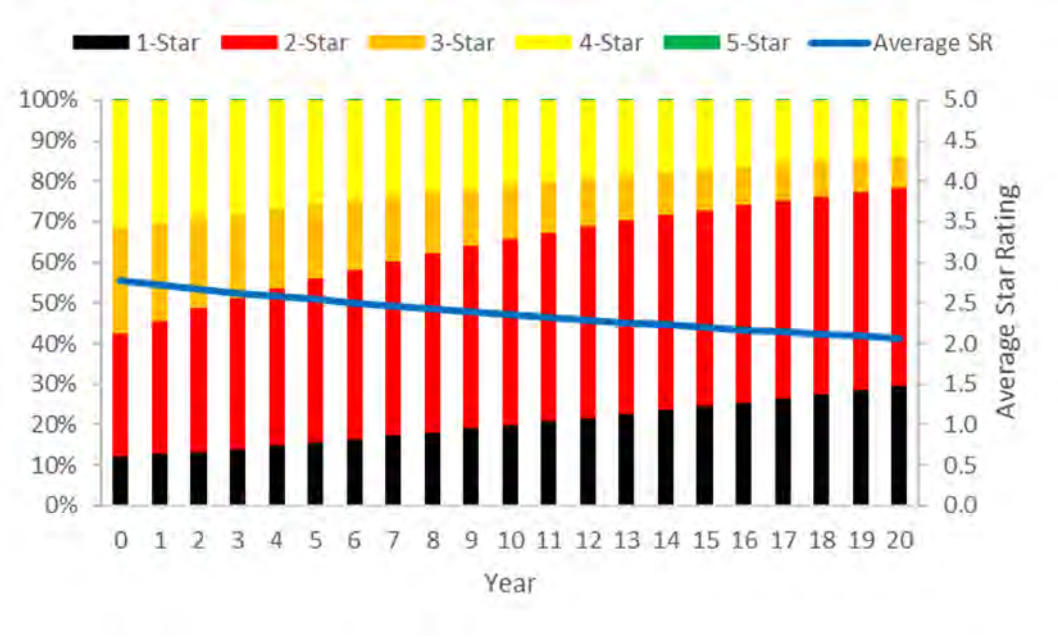
9.4.1 Road Management Assessment and Work Programme

9.4.1.1 Do Minimum

Year	Annual Costs (MYR 'mil)						Net Benefits* (MYR 'mil)	Asset Value (MYR 'mil)	Annual Road Works (km)			Road Condition	
	Rehab. (MYR 'mil)	Periodic Maint. (MYR 'mil)	Recurrent Maint. (MYR 'mil)	Road Agency (MYR 'mil)	Road Users (MYR 'mil)	Society (MYR 'mil)			Rehab. (km)	Periodic Maint. (km)	Recurrent Maint. (km)	Roughness per km (IRI)	Roughness per veh-km (IRI)
1	0.0	0.0	18.8	18.8	16,840	16,859	0	6,802	0	0	3,688	4.9	4.2
2	0.0	0.0	18.8	18.8	17,402	17,420	0	6,802	0	0	3,688	5.2	4.4
3	0.0	0.0	18.8	18.8	17,990	18,009	0	6,788	0	0	3,688	5.4	4.6
4	98.4	0.0	18.8	117.2	18,278	18,395	0	6,715	246	0	3,688	4.9	4.4
5	0.0	0.0	18.8	18.8	18,896	18,915	0	6,569	0	0	3,688	5.1	4.6
6	0.0	0.0	18.8	18.8	19,545	19,564	0	6,552	0	0	3,688	5.4	4.9
7	0.0	0.0	18.8	18.8	20,226	20,245	0	6,515	0	0	3,688	5.6	5.1
8	0.0	0.0	18.8	18.8	20,943	20,962	0	6,515	0	0	3,688	5.9	5.3
9	0.0	0.0	18.8	18.8	21,698	21,717	0	6,514	0	0	3,688	6.2	5.6
10	0.0	0.0	18.8	18.8	22,494	22,513	0	6,481	0	0	3,688	6.5	5.9
11	0.0	0.0	18.8	18.8	23,333	23,352	0	6,474	0	0	3,688	6.9	6.2
12	44.0	0.0	18.8	62.8	24,151	24,214	0	6,487	110	0	3,688	6.9	6.5
13	116.0	0.0	18.8	134.8	24,497	24,632	0	6,468	290	0	3,688	6.3	6.2
14	12.0	0.0	18.8	30.8	25,290	25,320	0	6,469	30	0	3,688	6.5	6.3
15	0.0	0.0	18.8	18.8	26,266	26,285	0	6,444	0	0	3,688	6.9	6.6
16	0.0	0.0	18.8	18.8	27,300	27,319	0	6,420	0	0	3,688	7.3	7.0
17	0.0	0.0	18.8	18.8	28,397	28,416	0	6,414	0	0	3,688	7.7	7.4
18	2.0	0.0	18.8	20.8	29,535	29,556	0	6,303	5	0	3,688	8.1	7.8
19	0.0	0.0	18.8	18.8	30,769	30,788	0	6,202	0	0	3,688	8.6	8.2
20	0.0	0.0	18.8	18.8	32,081	32,100	0	6,201	0	0	3,688	9.1	8.7
Years 1-5 Total	98.4	0.0	94.0	192.4	89,406	89,598	0	33,676	246	0	18,440		
Years 6-20 Total	174.0	0.0	282.1	456.1	376,526	376,982	0	96,460	435	0	55,320		
Years 1-20 Total	272.4	0.0	376.2	648.6	465,932	466,580	0	130,136	681	0	73,760		
Years 1-5 Total per Year	19.7	0.0	18.8	38.5	17,881	17,920	0	6,735	49	0	3,688		
Years 6-20 Total per Year	11.6	0.0	18.8	30.4	25,102	25,132	0	6,431	29	0	3,688		
Years 1-20 Total per Year	13.6	0.0	18.8	32.4	23,297	23,329	0	6,507	34	0	3,688		
PV at 12% (MYR 'mil)	115.5	0.0	157.4	272.9	172,985	173,258	0	55,249	289	0	30,853		
Rate of Return (%)							#NUM!						
Average (IRI)												6.5	6.0

* Comparison with Do Minimum Scenario

Appendix 10 Road Safety Degradation, *dRSR* (RSD)



Year	DeteriorationRate					Total	Star Rating per km
	2%	12%	4%	2%	0%		
	★	★★	★★★	★★★★	★★★★★		
0	444	1127	953	1163	1	**3688**	**2.8**
1	467	1219	885	1117	1	**3688**	**2.7**
2	491	1301	824	1072	1	**3688**	**2.7**
3	517	1373	768	1029	1	**3688**	**2.6**
4	544	1438	717	988	1	**3688**	**2.6**
5	573	1495	670	948	1	**3688**	**2.5**
6	603	1546	628	910	1	**3688**	**2.5**
7	634	1590	589	874	1	**3688**	**2.5**
8	666	1629	553	839	1	**3688**	**2.4**
9	698	1663	520	806	1	**3688**	**2.4**
10	732	1692	490	773	1	**3688**	**2.4**
11	765	1717	462	742	1	**3688**	**2.3**
12	800	1738	436	713	1	**3688**	**2.3**
13	835	1756	413	684	1	**3688**	**2.3**
14	870	1770	390	657	1	**3688**	**2.2**
15	905	1782	370	631	1	**3688**	**2.2**
16	941	1790	351	605	1	**3688**	**2.2**
17	977	1797	333	581	1	**3688**	**2.1**
18	1012	1801	316	558	1	**3688**	**2.1**
19	1048	1803	301	536	1	**3688**	**2.1**
20	1085	1803	286	514	1	**3688**	**2.1**

Appendix 11 Road Safety Assessment

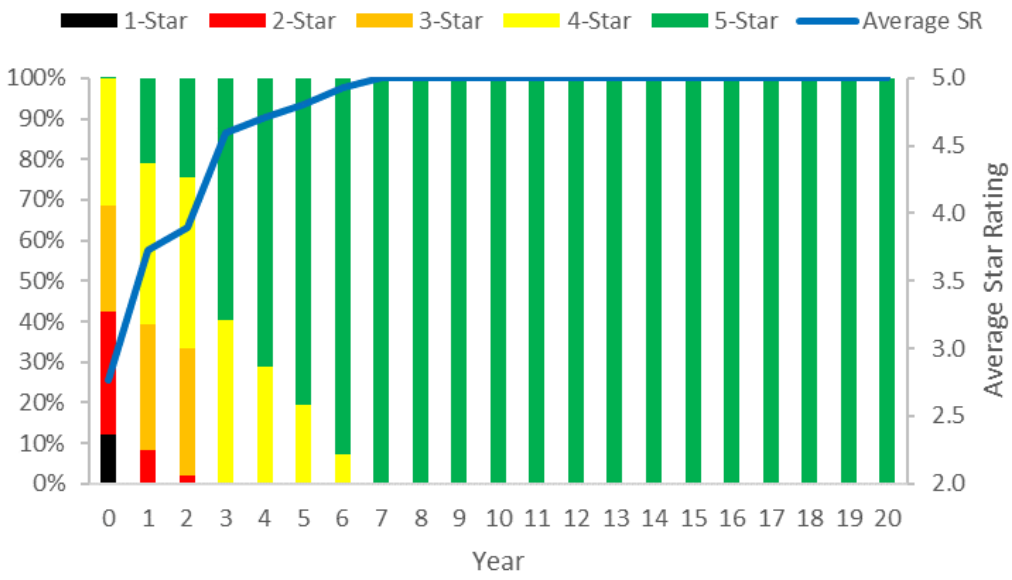
11.1 Case I: Benefit-Cost Ratio Strategy

11.1.1 Optimal +2

11.1.1.1 Countermeasure Effects (CE)

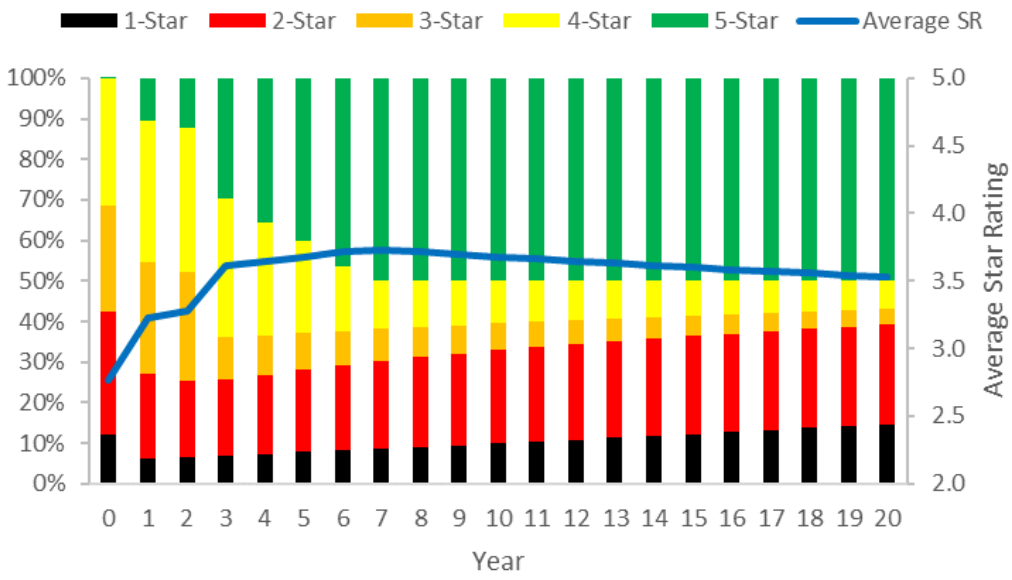
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	0	0	0	0	0	**0**
1	9	107	19	3151	20	**3305**
2	6	127	19	79	40	**270**
3	6	107	19	1165	20	**1316**
4	6	107	19	293	20	**444**
5	6	107	19	215	20	**366**
6	6	107	19	325	20	**476**
7	6	107	19	176	20	**327**
8	6	107	19	837	20	**988**
9	6	107	19	113	20	**264**
10	6	107	19	1764	20	**1915**
11	6	107	19	583	20	**734**
12	6	107	19	176	20	**327**
13	6	107	19	215	20	**366**
14	6	107	19	0	20	**151**
15	6	107	19	982	20	**1133**
16	6	107	19	3	20	**154**
17	6	107	19	637	20	**788**
18	6	107	19	1382	20	**1533**
19	6	107	19	469	20	**620**
20	6	107	19	0	20	**151**

11.1.1.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	★	★★	☆☆☆	☆☆☆☆	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	0	310	1146	1462	771	**3.7**
2	0	80	1146	1559	904	**3.9**
3	0	0	0	1489	2200	**4.6**
4	0	0	0	1065	2624	**4.7**
5	0	0	0	719	2970	**4.8**
6	0	0	0	263	3426	**4.9**
7	0	0	0	0	3688	**5.0**
8	0	0	0	0	3688	**5.0**
9	0	0	0	0	3688	**5.0**
10	0	0	0	0	3688	**5.0**
11	0	0	0	0	3688	**5.0**
12	0	0	0	0	3688	**5.0**
13	0	0	0	0	3688	**5.0**
14	0	0	0	0	3688	**5.0**
15	0	0	0	0	3688	**5.0**
16	0	0	0	0	3688	**5.0**
17	0	0	0	0	3688	**5.0**
18	0	0	0	0	3688	**5.0**
19	0	0	0	0	3688	**5.0**
20	0	0	0	0	3688	**5.0**

11.1.1.3 Annual Road Safety Rating (RSR_{n+1})



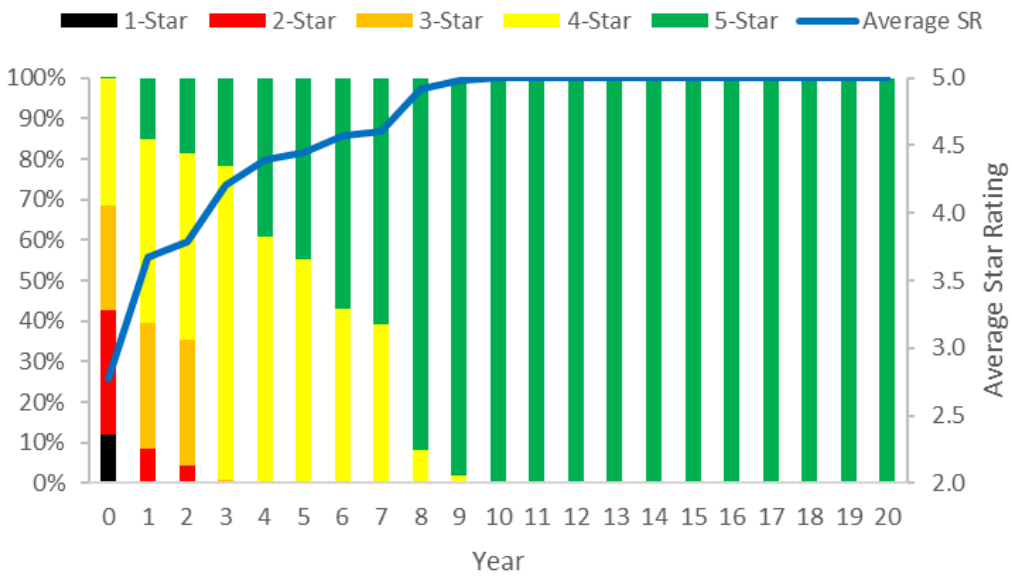
Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	233	764	1015	1289	386	**3.2**
2	245	690	985	1315	452	**3.3**
3	258	687	384	1259	1100	**3.6**
4	272	719	358	1026	1312	**3.6**
5	287	748	335	833	1485	**3.7**
6	302	773	314	586	1713	**3.7**
7	317	795	294	437	1845	**3.7**
8	333	815	277	420	1845	**3.7**
9	349	831	260	403	1845	**3.7**
10	366	846	245	387	1845	**3.7**
11	383	859	231	371	1845	**3.7**
12	400	869	218	356	1845	**3.6**
13	417	878	206	342	1845	**3.6**
14	435	885	195	328	1845	**3.6**
15	453	891	185	315	1845	**3.6**
16	470	895	175	303	1845	**3.6**
17	488	898	166	291	1845	**3.6**
18	506	900	158	279	1845	**3.6**
19	524	901	150	268	1845	**3.5**
20	542	901	143	257	1845	**3.5**

11.1.2 Optimal

11.1.2.1 Countermeasure Effects (CE)

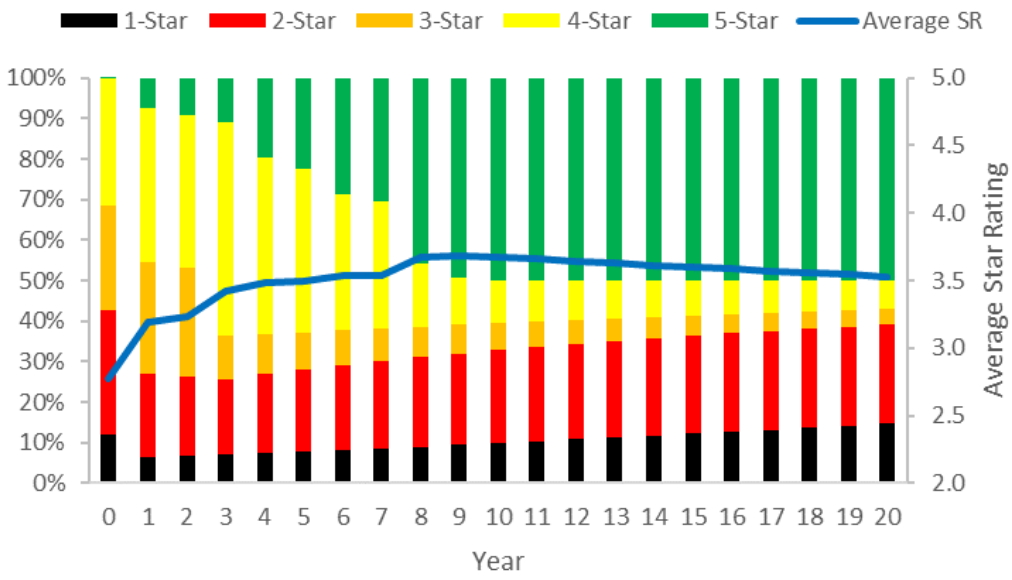
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	**0**	**0**	**0**	**0**	**0**	**0**
1	9	107	19	2936	20	**3090**
2	6	127	19	0	40	**191**
3	6	107	19	1165	20	**1316**
4	6	107	19	508	20	**659**
5	6	107	19	79	20	**230**
6	6	107	19	325	20	**476**
7	6	107	19	0	20	**151**
8	6	107	19	1013	20	**1164**
9	6	107	19	110	20	**261**
10	6	107	19	1662	20	**1813**
11	6	107	19	586	20	**737**
12	6	107	19	65	20	**216**
13	6	107	19	173	20	**324**
14	6	107	19	79	20	**230**
15	6	107	19	1158	20	**1309**
16	6	107	19	0	20	**151**
17	6	107	19	572	20	**723**
18	6	107	19	1130	20	**1281**
19	6	107	19	293	20	**444**
20	6	107	19	218	20	**369**

11.1.2.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	★	★★	☆☆☆	☆☆☆☆	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	0	310	1146	1677	556	**3.7**
2	0	159	1146	1695	689	**3.8**
3	0	0	37	2851	801	**4.2**
4	0	0	0	2248	1440	**4.4**
5	0	0	0	2038	1650	**4.4**
6	0	0	0	1582	2106	**4.6**
7	0	0	0	1451	2237	**4.6**
8	0	0	0	307	3381	**4.9**
9	0	0	0	66	3622	**5.0**
10	0	0	0	0	3688	**5.0**
11	0	0	0	0	3688	**5.0**
12	0	0	0	0	3688	**5.0**
13	0	0	0	0	3688	**5.0**
14	0	0	0	0	3688	**5.0**
15	0	0	0	0	3688	**5.0**
16	0	0	0	0	3688	**5.0**
17	0	0	0	0	3688	**5.0**
18	0	0	0	0	3688	**5.0**
19	0	0	0	0	3688	**5.0**
20	0	0	0	0	3688	**5.0**

11.1.2.3 Annual Road Safety Rating (RSR_{n+1})



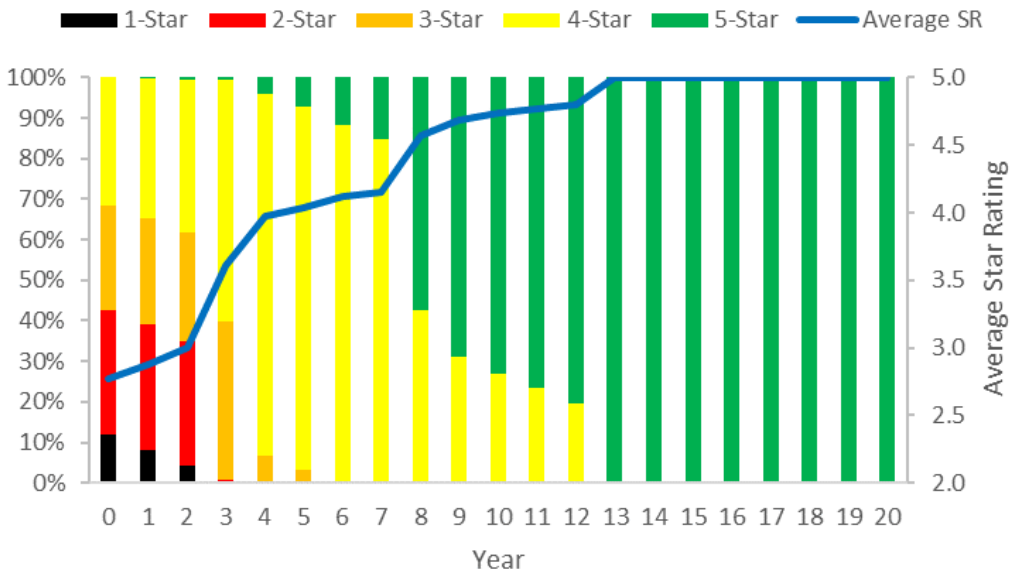
Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	233	764	1015	1397	279	**3.2**
2	245	730	985	1383	345	**3.2**
3	258	687	402	1940	401	**3.4**
4	272	719	358	1618	721	**3.5**
5	287	748	335	1493	826	**3.5**
6	302	773	314	1246	1054	**3.5**
7	317	795	294	1163	1119	**3.5**
8	333	815	277	573	1691	**3.7**
9	349	831	260	436	1812	**3.7**
10	366	846	245	387	1845	**3.7**
11	383	859	231	371	1845	**3.7**
12	400	869	218	356	1845	**3.6**
13	417	878	206	342	1845	**3.6**
14	435	885	195	328	1845	**3.6**
15	453	891	185	315	1845	**3.6**
16	470	895	175	303	1845	**3.6**
17	488	898	166	291	1845	**3.6**
18	506	900	158	279	1845	**3.6**
19	524	901	150	268	1845	**3.5**
20	542	901	143	257	1845	**3.5**

11.1.3 Optimal -2

11.1.3.1 Countermeasure Effects (CE)

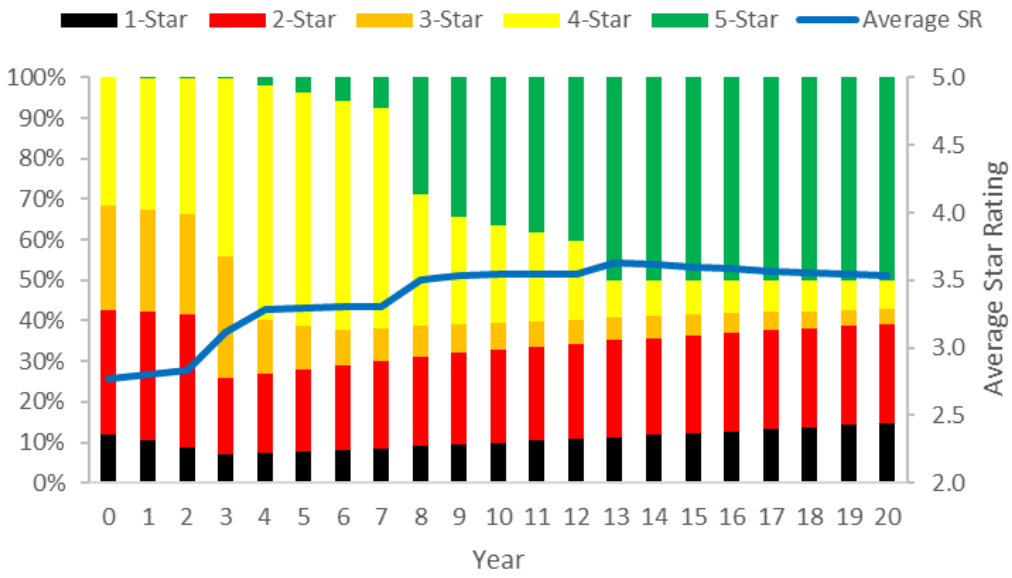
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	**0**	**0**	**0**	**0**	**0**	**0**
1	9	107	19	5	20	**159**
2	6	127	19	0	40	**191**
3	6	107	19	1853	20	**2004**
4	6	107	19	1083	20	**1234**
5	6	107	19	0	20	**151**
6	6	107	19	30	20	**181**
7	6	107	19	0	20	**151**
8	6	107	19	1428	20	**1579**
9	6	107	19	290	20	**441**
10	6	107	19	30	20	**181**
11	6	107	19	0	20	**151**
12	6	107	19	0	20	**151**
13	6	107	19	1234	20	**1385**
14	6	107	19	0	20	**151**
15	6	107	19	320	20	**471**
16	6	107	19	0	20	**151**
17	6	107	19	1130	20	**1281**
18	6	107	19	293	20	**444**
19	6	107	19	5	20	**156**
20	6	107	19	0	20	**151**

11.1.3.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	1-Star	2-Star	3-Star	4-Star	5-Star	Average SR
0	444	1127	953	1163	1	**2.8**
1	305	1132	972	1270	10	**2.9**
2	154	1132	990	1396	16	**3.0**
3	0	23	1443	2201	22	**3.6**
4	0	0	252	3284	153	**4.0**
5	0	0	121	3302	266	**4.0**
6	0	0	0	3262	427	**4.1**
7	0	0	0	3131	558	**4.2**
8	0	0	0	1572	2117	**4.6**
9	0	0	0	1151	2538	**4.7**
10	0	0	0	990	2699	**4.7**
11	0	0	0	859	2830	**4.8**
12	0	0	0	728	2961	**4.8**
13	0	0	0	0	3688	**5.0**
14	0	0	0	0	3688	**5.0**
15	0	0	0	0	3688	**5.0**
16	0	0	0	0	3688	**5.0**
17	0	0	0	0	3688	**5.0**
18	0	0	0	0	3688	**5.0**
19	0	0	0	0	3688	**5.0**
20	0	0	0	0	3688	**5.0**

11.1.3.3 Annual Road Safety Rating (RSR_{n+1})



Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	**444**	**1127**	**953**	**1163**	**1**	**2.8**
1	386	1175	928	1193	6	**2.8**
2	322	1216	907	1234	9	**2.8**
3	258	698	1105	1615	12	**3.1**
4	272	719	484	2136	77	**3.3**
5	287	748	395	2125	133	**3.3**
6	302	773	314	2086	214	**3.3**
7	317	795	294	2002	279	**3.3**
8	333	815	277	1205	1059	**3.5**
9	349	831	260	978	1269	**3.5**
10	366	846	245	881	1350	**3.5**
11	383	859	231	800	1415	**3.5**
12	400	869	218	720	1481	**3.5**
13	417	878	206	342	1845	**3.6**
14	435	885	195	328	1845	**3.6**
15	453	891	185	315	1845	**3.6**
16	470	895	175	303	1845	**3.6**
17	488	898	166	291	1845	**3.6**
18	506	900	158	279	1845	**3.6**
19	524	901	150	268	1845	**3.5**
20	542	901	143	257	1845	**3.5**

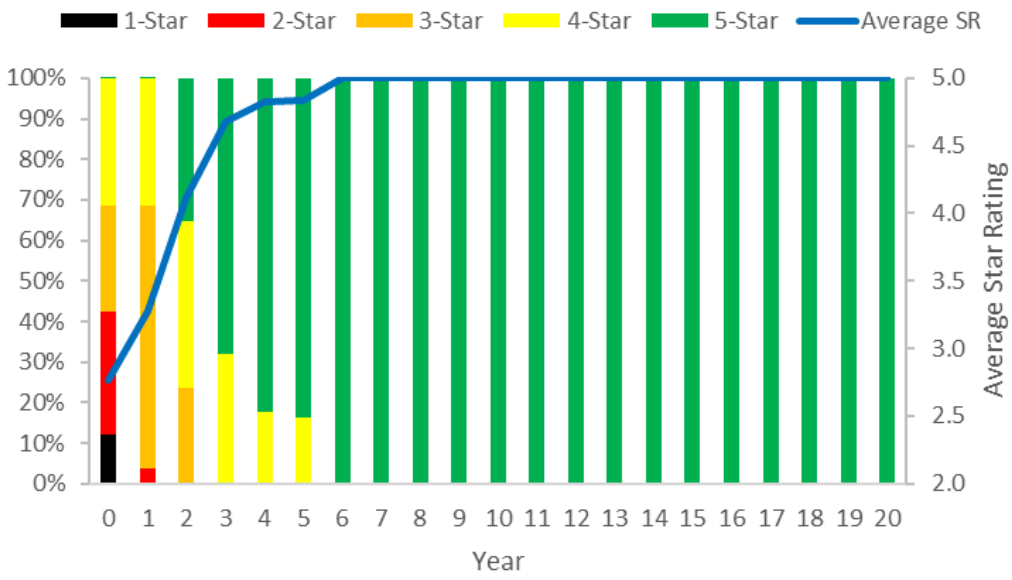
11.2 Case II: Treatment-Based Strategy

11.2.1 Custom +2

11.2.1.1 Countermeasure Effects (CE)

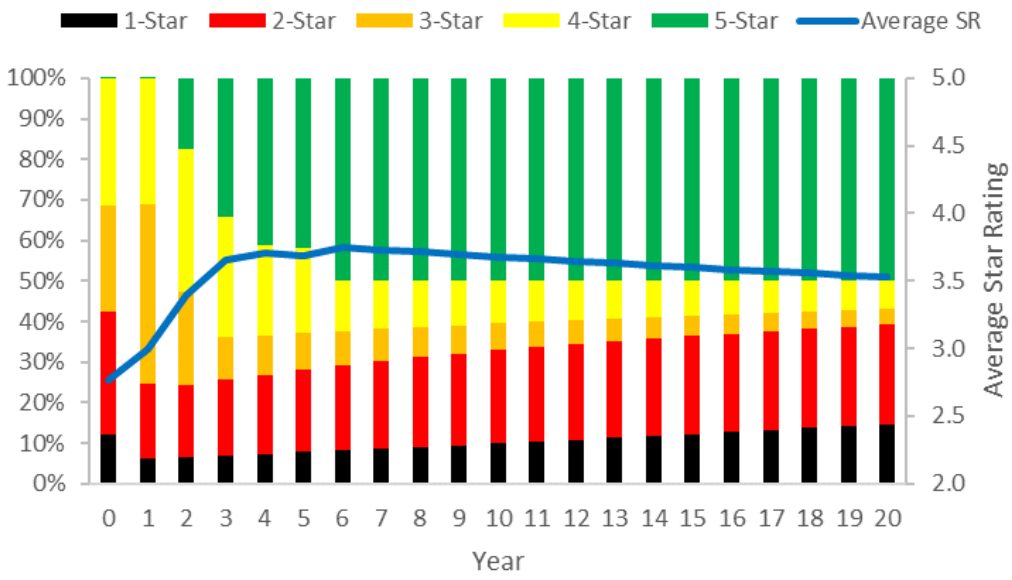
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	0	0	0	0	0	**0**
1	0	0	309	2090	0	**2399**
2	0	1238	61	361	0	**1659**
3	0	523	0	1033	0	**1556**
4	0	59	0	461	0	**520**
5	0	55	0	0	0	**55**
6	0	55	0	881	0	**936**
7	0	55	0	172	0	**227**
8	0	55	0	638	0	**693**
9	0	55	0	250	0	**305**
10	0	55	0	1039	0	**1094**
11	17	0	0	216	0	**233**
12	14	0	0	90	0	**104**
13	14	0	0	903	0	**917**
14	14	0	0	717	0	**731**
15	14	0	0	385	0	**399**
16	14	0	0	75	0	**89**
17	14	0	0	431	0	**445**
18	14	0	0	1087	0	**1101**
19	7	0	0	95	221	**324**
20	0	0	0	160	199	**359**

11.2.1.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	★	★★	☆☆☆	☆☆☆☆	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	0	135	2389	1163	1	**3.3**
2	0	0	865	1524	1299	**4.1**
3	0	0	0	1175	2513	**4.7**
4	0	0	0	656	3032	**4.8**
5	0	0	0	600	3088	**4.8**
6	0	0	0	0	3688	**5.0**
7	0	0	0	0	3688	**5.0**
8	0	0	0	0	3688	**5.0**
9	0	0	0	0	3688	**5.0**
10	0	0	0	0	3688	**5.0**
11	0	0	0	0	3688	**5.0**
12	0	0	0	0	3688	**5.0**
13	0	0	0	0	3688	**5.0**
14	0	0	0	0	3688	**5.0**
15	0	0	0	0	3688	**5.0**
16	0	0	0	0	3688	**5.0**
17	0	0	0	0	3688	**5.0**
18	0	0	0	0	3688	**5.0**
19	0	0	0	0	3688	**5.0**
20	0	0	0	0	3688	**5.0**

11.2.1.3 Annual Road Safety Rating (RSR_{n+1})



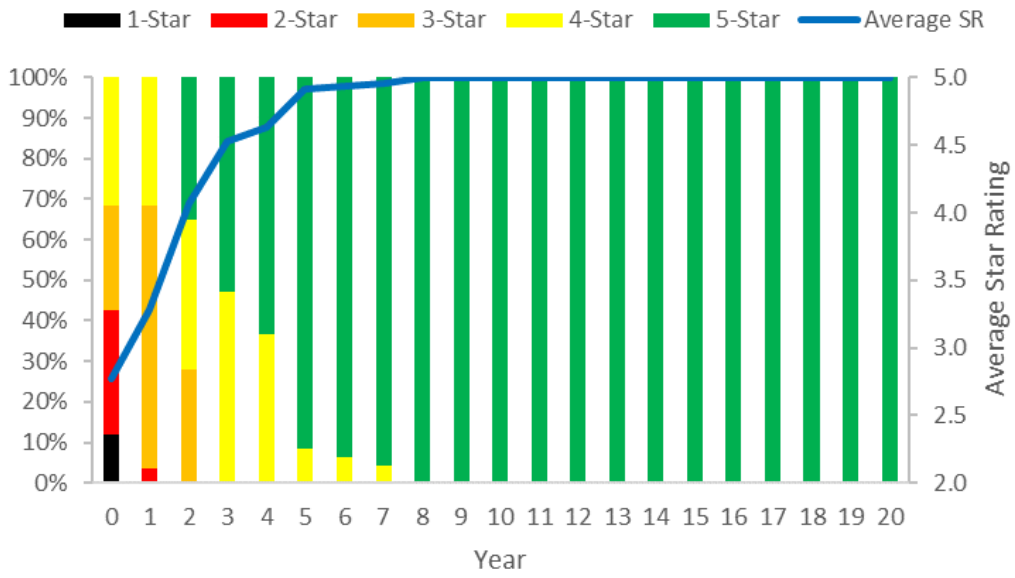
Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	233	677	1637	1140	1	**3.0**
2	245	650	844	1298	650	**3.4**
3	258	687	384	1102	1257	**3.7**
4	272	719	358	822	1517	**3.7**
5	287	748	335	774	1544	**3.7**
6	302	773	314	455	1845	**3.8**
7	317	795	294	437	1845	**3.7**
8	333	815	277	420	1845	**3.7**
9	349	831	260	403	1845	**3.7**
10	366	846	245	387	1845	**3.7**
11	383	859	231	371	1845	**3.7**
12	400	869	218	356	1845	**3.6**
13	417	878	206	342	1845	**3.6**
14	435	885	195	328	1845	**3.6**
15	453	891	185	315	1845	**3.6**
16	470	895	175	303	1845	**3.6**
17	488	898	166	291	1845	**3.6**
18	506	900	158	279	1845	**3.6**
19	524	901	150	268	1845	**3.5**
20	542	901	143	257	1845	**3.5**

11.2.2 Custom

11.2.2.1 Countermeasure Effects (CE)

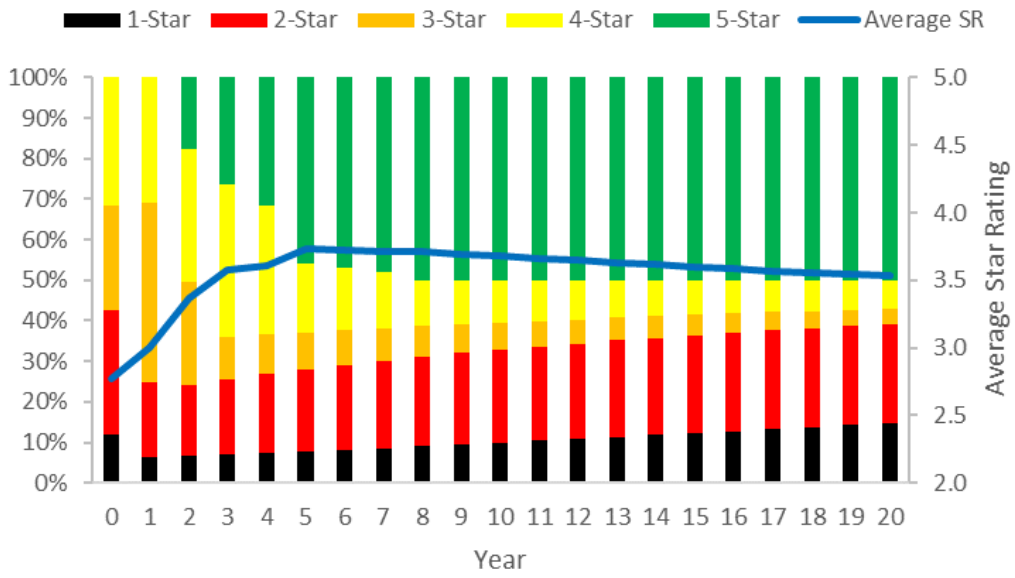
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	0	0	0	0	0	**0**
1	0	0	309	525	0	**834**
2	0	1238	61	189	0	**1487**
3	0	523	0	640	0	**1163**
4	0	59	0	326	0	**385**
5	0	55	0	986	0	**1041**
6	0	55	0	30	0	**85**
7	0	55	0	19	0	**74**
8	0	55	0	651	0	**706**
9	0	55	0	148	0	**203**
10	0	55	0	238	0	**293**
11	17	0	0	880	0	**897**
12	14	0	0	81	0	**95**
13	14	0	0	434	0	**448**
14	14	0	0	120	0	**134**
15	14	0	0	436	0	**450**
16	14	0	0	3	0	**17**
17	14	0	0	585	0	**599**
18	14	0	0	333	0	**347**
19	7	0	0	10	221	**239**
20	0	0	0	20	199	**219**

11.2.2.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	★	★★	☆☆☆	☆☆☆☆	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	0	135	2389	1163	1	**3.3**
2	0	0	1037	1352	1299	**4.1**
3	0	0	0	1740	1948	**4.5**
4	0	0	0	1356	2332	**4.6**
5	0	0	0	314	3374	**4.9**
6	0	0	0	229	3459	**4.9**
7	0	0	0	155	3533	**5.0**
8	0	0	0	0	3688	**5.0**
9	0	0	0	0	3688	**5.0**
10	0	0	0	0	3688	**5.0**
11	0	0	0	0	3688	**5.0**
12	0	0	0	0	3688	**5.0**
13	0	0	0	0	3688	**5.0**
14	0	0	0	0	3688	**5.0**
15	0	0	0	0	3688	**5.0**
16	0	0	0	0	3688	**5.0**
17	0	0	0	0	3688	**5.0**
18	0	0	0	0	3688	**5.0**
19	0	0	0	0	3688	**5.0**
20	0	0	0	0	3688	**5.0**

11.2.2.3 Annual Road Safety Rating (RSR_{n+1})



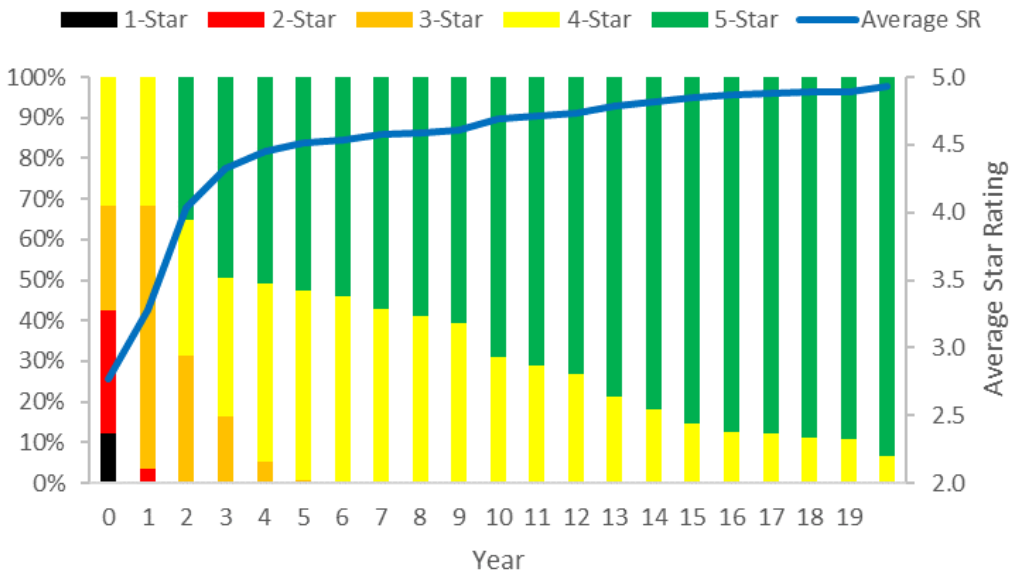
Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	233	677	1637	1140	1	**3.0**
2	245	650	930	1212	650	**3.4**
3	258	687	384	1385	974	**3.6**
4	272	719	358	1172	1167	**3.6**
5	287	748	335	631	1687	**3.7**
6	302	773	314	570	1730	**3.7**
7	317	795	294	515	1767	**3.7**
8	333	815	277	420	1845	**3.7**
9	349	831	260	403	1845	**3.7**
10	366	846	245	387	1845	**3.7**
11	383	859	231	371	1845	**3.7**
12	400	869	218	356	1845	**3.6**
13	417	878	206	342	1845	**3.6**
14	435	885	195	328	1845	**3.6**
15	453	891	185	315	1845	**3.6**
16	470	895	175	303	1845	**3.6**
17	488	898	166	291	1845	**3.6**
18	506	900	158	279	1845	**3.6**
19	524	901	150	268	1845	**3.5**
20	542	901	143	257	1845	**3.5**

11.2.3 Custom -2

11.2.3.1 Countermeasure Effects (CE)

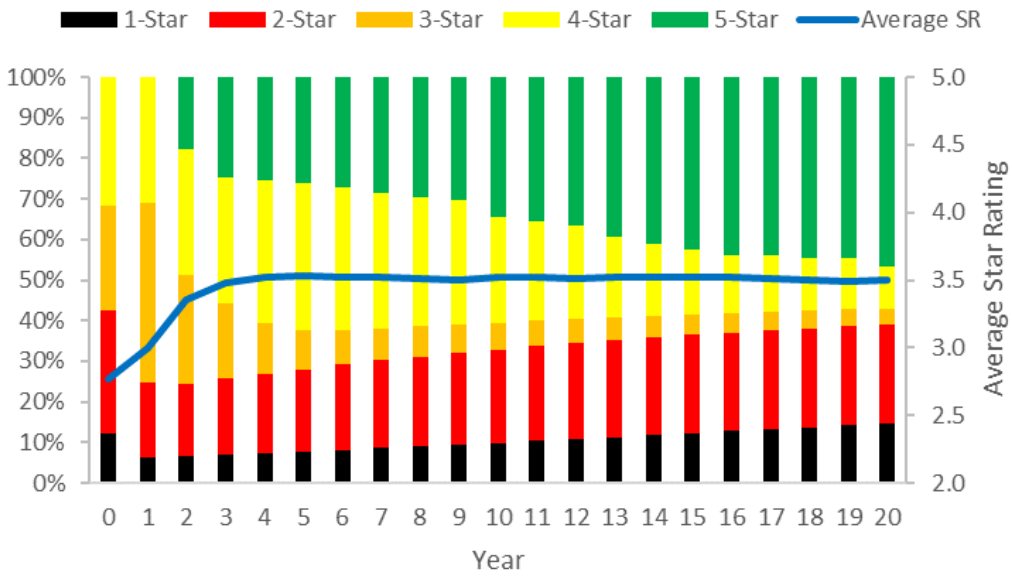
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	0	0	0	0	0	**0**
1	0	0	309	151	0	**460**
2	0	1238	61	65	0	**1363**
3	0	523	0	34	0	**557**
4	0	59	0	350	0	**409**
5	0	55	0	114	0	**169**
6	0	55	0	0	0	**55**
7	0	55	0	65	0	**120**
8	0	55	0	10	0	**65**
9	0	55	0	0	0	**55**
10	0	55	0	260	0	**315**
11	17	0	0	63	0	**80**
12	14	0	0	64	0	**78**
13	14	0	0	189	0	**203**
14	14	0	0	100	0	**114**
15	14	0	0	109	0	**123**
16	14	0	0	65	0	**79**
17	14	0	0	0	0	**14**
18	14	0	0	25	0	**39**
19	7	0	0	10	221	**239**
20	0	0	0	153	199	**352**

11.2.3.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	1-Star	2-Star	3-Star	4-Star	5-Star	Average SR
0	444	1127	953	1163	1	**2.8**
1	0	135	2389	1163	1	**3.3**
2	0	0	1161	1228	1299	**4.0**
3	0	0	604	1262	1822	**4.3**
4	0	0	195	1612	1881	**4.5**
5	0	0	26	1726	1936	**4.5**
6	0	0	0	1697	1991	**4.5**
7	0	0	0	1577	2111	**4.6**
8	0	0	0	1512	2176	**4.6**
9	0	0	0	1456	2232	**4.6**
10	0	0	0	1141	2547	**4.7**
11	0	0	0	1062	2626	**4.7**
12	0	0	0	983	2705	**4.7**
13	0	0	0	780	2908	**4.8**
14	0	0	0	666	3022	**4.8**
15	0	0	0	543	3145	**4.9**
16	0	0	0	464	3224	**4.9**
17	0	0	0	449	3239	**4.9**
18	0	0	0	410	3278	**4.9**
19	0	0	0	393	3295	**4.9**
20	0	0	0	240	3448	**4.9**

11.2.3.3 Annual Road Safety Rating (RSR_{n+1})



Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	233	677	1637	1140	1	**3.0**
2	245	650	992	1150	650	**3.4**
3	258	687	686	1146	911	**3.5**
4	272	719	456	1300	941	**3.5**
5	287	748	348	1337	968	**3.5**
6	302	773	314	1304	996	**3.5**
7	317	795	294	1225	1056	**3.5**
8	333	815	277	1175	1089	**3.5**
9	349	831	260	1131	1116	**3.5**
10	366	846	245	957	1274	**3.5**
11	383	859	231	902	1314	**3.5**
12	400	869	218	848	1353	**3.5**
13	417	878	206	732	1454	**3.5**
14	435	885	195	661	1512	**3.5**
15	453	891	185	587	1573	**3.5**
16	470	895	175	535	1613	**3.5**
17	488	898	166	515	1620	**3.5**
18	506	900	158	484	1639	**3.5**
19	524	901	150	464	1648	**3.5**
20	542	901	143	377	1724	**3.5**

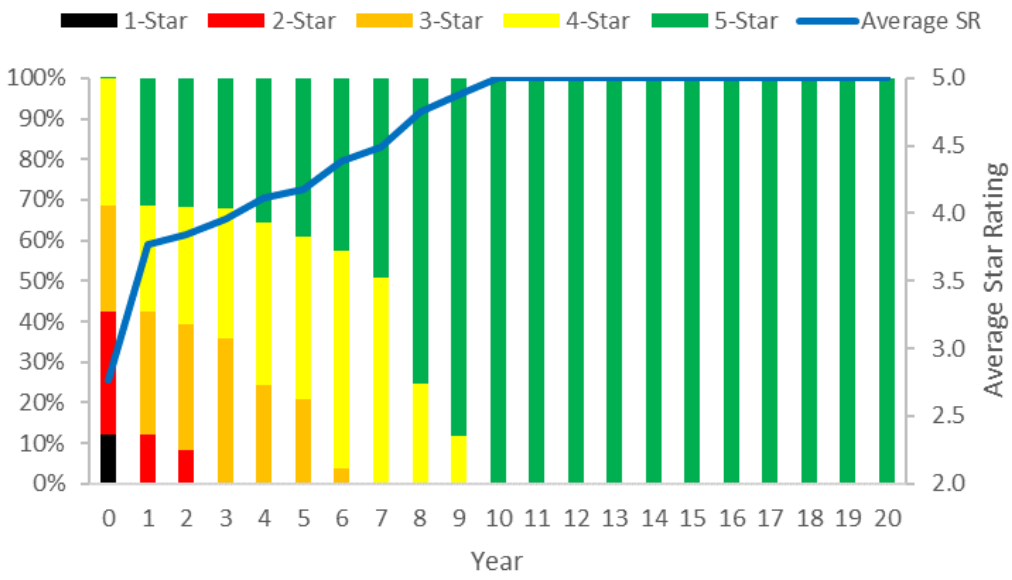
11.3 Case III: Average Budget Strategy

11.3.1 Very High

11.3.1.1 Countermeasure Effects (CE)

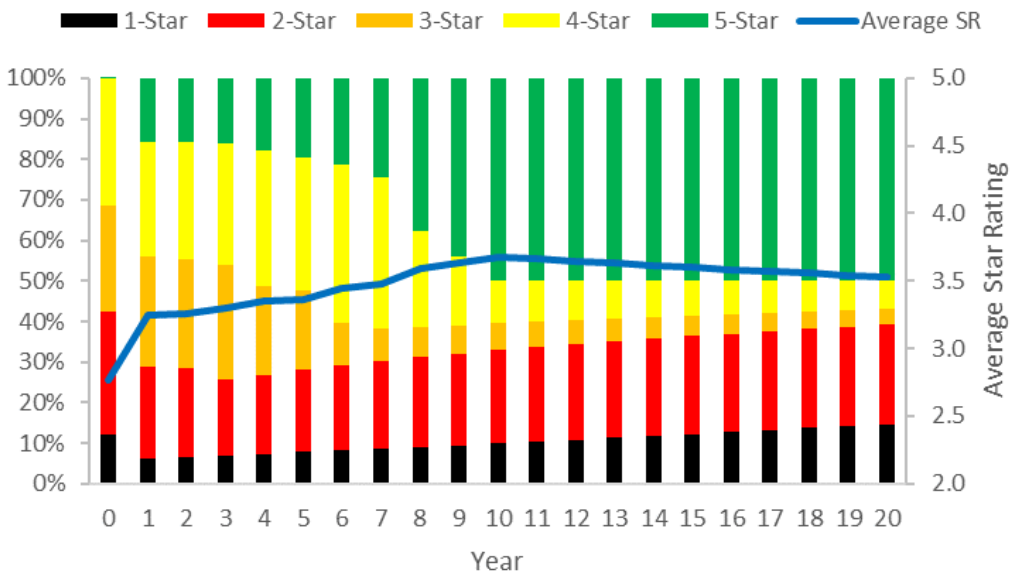
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	**0**	**0**	**0**	**0**	**0**	**0**
1	**0**	**0**	**0**	3230	20	**3250**
2	9	107	19	0	20	**154**
3	6	127	19	1380	30	**1561**
4	6	107	19	293	30	**454**
5	6	107	19	0	20	**151**
6	6	107	19	501	20	**652**
7	6	107	19	82	20	**233**
8	6	107	19	837	20	**988**
9	6	107	19	348	20	**499**
10	6	107	19	1662	20	**1813**
11	6	107	19	759	20	**910**
12	6	107	19	0	20	**151**
13	6	107	19	0	20	**151**
14	6	107	19	82	20	**233**
15	6	107	19	1047	20	**1198**
16	6	107	19	173	20	**324**
17	6	107	19	963	20	**1114**
18	6	107	19	1130	20	**1281**
19	6	107	19	293	20	**444**
20	6	107	19	0	20	**151**

11.3.1.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	0	444	1127	953	1164	**3.8**
2	0	310	1146	1060	1173	**3.8**
3	0	0	1323	1186	1179	**4.0**
4	0	0	899	1479	1310	**4.1**
5	0	0	768	1479	1441	**4.2**
6	0	0	136	1980	1572	**4.4**
7	0	0	0	1880	1809	**4.5**
8	0	0	0	912	2777	**4.8**
9	0	0	0	433	3256	**4.9**
10	0	0	0	0	3688	**5.0**
11	0	0	0	0	3688	**5.0**
12	0	0	0	0	3688	**5.0**
13	0	0	0	0	3688	**5.0**
14	0	0	0	0	3688	**5.0**
15	0	0	0	0	3688	**5.0**
16	0	0	0	0	3688	**5.0**
17	0	0	0	0	3688	**5.0**
18	0	0	0	0	3688	**5.0**
19	0	0	0	0	3688	**5.0**
20	0	0	0	0	3688	**5.0**

11.3.1.3 Annual Road Safety Rating (RSR_{n+1})



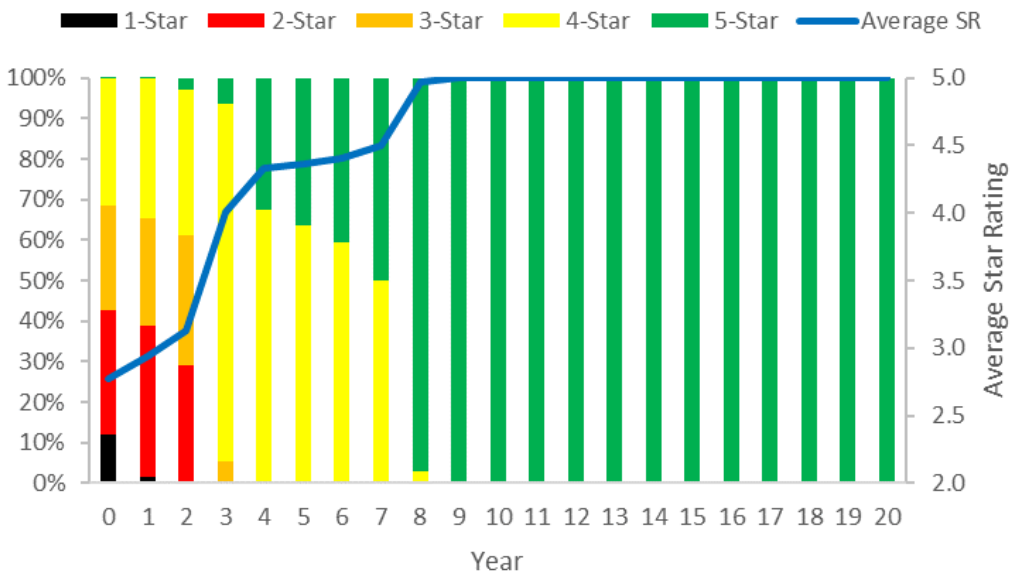
Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	233	831	1006	1035	583	**3.2**
2	245	805	985	1066	587	**3.3**
3	258	687	1045	1108	590	**3.3**
4	272	719	808	1233	656	**3.3**
5	287	748	719	1214	721	**3.4**
6	302	773	382	1445	787	**3.4**
7	317	795	294	1377	905	**3.5**
8	333	815	277	875	1389	**3.6**
9	349	831	260	619	1628	**3.6**
10	366	846	245	387	1845	**3.7**
11	383	859	231	371	1845	**3.7**
12	400	869	218	356	1845	**3.6**
13	417	878	206	342	1845	**3.6**
14	435	885	195	328	1845	**3.6**
15	453	891	185	315	1845	**3.6**
16	470	895	175	303	1845	**3.6**
17	488	898	166	291	1845	**3.6**
18	506	900	158	279	1845	**3.6**
19	524	901	150	268	1845	**3.5**
20	542	901	143	257	1845	**3.5**

11.3.2 Medium

11.3.2.1 Countermeasure Effects (CE)

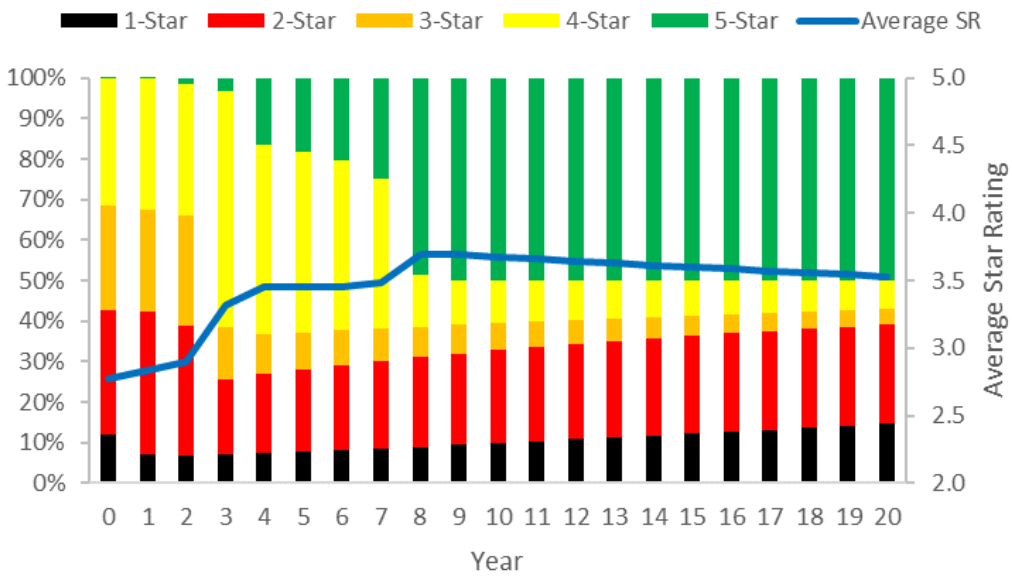
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	0	0	0	0	0	**0**
1	9	107	19	246	20	**400**
2	6	127	19	215	20	**386**
3	6	107	19	1932	30	**2093**
4	6	107	19	842	30	**1003**
5	6	107	19	0	20	**151**
6	6	107	19	30	20	**181**
7	6	107	19	215	20	**366**
8	6	107	19	1604	20	**1755**
9	6	107	19	290	20	**441**
10	6	107	19	33	20	**184**
11	6	107	19	65	20	**216**
12	6	107	19	252	20	**403**
13	6	107	19	1234	20	**1385**
14	6	107	19	176	20	**327**
15	6	107	19	320	20	**471**
16	6	107	19	215	20	**366**
17	6	107	19	1130	20	**1281**
18	6	107	19	296	20	**447**
19	6	107	19	70	20	**221**
20	6	107	19	0	20	**151**

11.3.2.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	64	1373	972	1270	10	**2.9**
2	0	1071	1187	1328	103	**3.1**
3	0	0	195	3260	234	**4.0**
4	0	0	0	2481	1207	**4.3**
5	0	0	0	2350	1338	**4.4**
6	0	0	0	2189	1499	**4.4**
7	0	0	0	1843	1845	**4.5**
8	0	0	0	108	3580	**5.0**
9	0	0	0	0	3688	**5.0**
10	0	0	0	0	3688	**5.0**
11	0	0	0	0	3688	**5.0**
12	0	0	0	0	3688	**5.0**
13	0	0	0	0	3688	**5.0**
14	0	0	0	0	3688	**5.0**
15	0	0	0	0	3688	**5.0**
16	0	0	0	0	3688	**5.0**
17	0	0	0	0	3688	**5.0**
18	0	0	0	0	3688	**5.0**
19	0	0	0	0	3688	**5.0**
20	0	0	0	0	3688	**5.0**

11.3.2.3 Annual Road Safety Rating (RSR_{n+1})



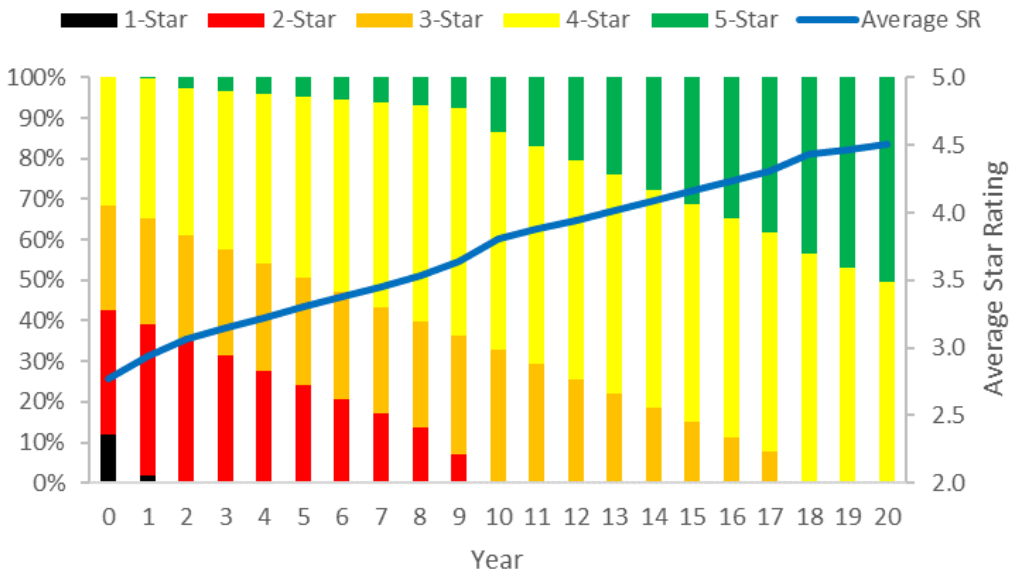
Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	265	1296	928	1193	6	**2.8**
2	245	1186	1005	1200	52	**2.9**
3	258	687	481	2144	118	**3.3**
4	272	719	358	1734	604	**3.5**
5	287	748	335	1649	670	**3.5**
6	302	773	314	1550	750	**3.5**
7	317	795	294	1359	923	**3.5**
8	333	815	277	474	1791	**3.7**
9	349	831	260	403	1845	**3.7**
10	366	846	245	387	1845	**3.7**
11	383	859	231	371	1845	**3.7**
12	400	869	218	356	1845	**3.6**
13	417	878	206	342	1845	**3.6**
14	435	885	195	328	1845	**3.6**
15	453	891	185	315	1845	**3.6**
16	470	895	175	303	1845	**3.6**
17	488	898	166	291	1845	**3.6**
18	506	900	158	279	1845	**3.6**
19	524	901	150	268	1845	**3.5**
20	542	901	143	257	1845	**3.5**

11.3.3 Very Low

11.3.3.1 Countermeasure Effects (CE)

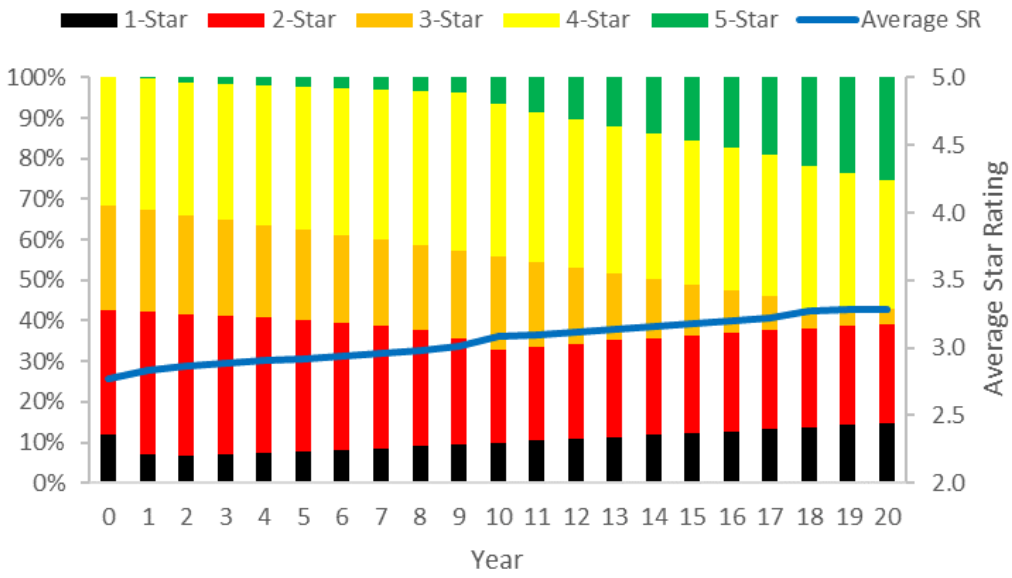
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	9	107	19	246	20	**400**
1	6	127	19	0	20	**171**
2	6	107	19	0	30	**161**
3	6	107	19	0	30	**161**
4	6	107	19	0	20	**151**
5	6	107	19	0	20	**151**
6	6	107	19	0	20	**151**
7	6	107	19	0	20	**151**
8	6	107	19	110	20	**261**
9	6	107	19	320	20	**471**
10	6	107	19	0	20	**151**
11	6	107	19	0	20	**151**
12	6	107	19	0	20	**151**
13	6	107	19	5	20	**156**
14	6	107	19	0	20	**151**
15	6	107	19	0	20	**151**
16	6	107	19	0	20	**151**
17	6	107	19	215	20	**366**
18	6	107	19	0	20	**151**
19	6	107	19	0	20	**151**
20	6	107	19	0	20	**151**

11.3.3.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	1-Star	2-Star	3-Star	4-Star	5-Star	Average SR
0	444	1127	953	1163	1	**2.8**
1	64	1373	972	1270	10	**2.9**
2	0	1286	972	1328	103	**3.1**
3	0	1155	972	1434	128	**3.1**
4	0	1024	972	1541	152	**3.2**
5	0	893	972	1647	177	**3.3**
6	0	762	972	1754	201	**3.4**
7	0	631	972	1860	226	**3.5**
8	0	500	972	1967	250	**3.5**
9	0	259	1082	2073	275	**3.6**
10	0	0	1210	1988	491	**3.8**
11	0	0	1079	1988	622	**3.9**
12	0	0	948	1988	753	**3.9**
13	0	0	817	1988	884	**4.0**
14	0	0	681	1988	1020	**4.1**
15	0	0	550	1988	1151	**4.2**
16	0	0	419	1988	1282	**4.2**
17	0	0	288	1988	1413	**4.3**
18	0	0	0	2086	1603	**4.4**
19	0	0	0	1955	1734	**4.5**
20	0	0	0	1824	1865	**4.5**

11.3.3.3 Annual Road Safety Rating (RSR_{n+1})



Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	265	1296	928	1193	6	**2.8**
2	245	1293	898	1200	52	**2.9**
3	258	1264	870	1232	64	**2.9**
4	272	1231	844	1264	77	**2.9**
5	287	1194	821	1298	89	**2.9**
6	302	1154	800	1332	101	**2.9**
7	317	1111	780	1367	113	**3.0**
8	333	1065	762	1403	126	**3.0**
9	349	961	801	1439	138	**3.0**
10	366	846	850	1380	246	**3.1**
11	383	859	770	1365	312	**3.1**
12	400	869	692	1350	377	**3.1**
13	417	878	615	1336	443	**3.1**
14	435	885	535	1322	511	**3.2**
15	453	891	460	1309	576	**3.2**
16	470	895	385	1296	642	**3.2**
17	488	898	310	1284	707	**3.2**
18	506	900	158	1322	802	**3.3**
19	524	901	150	1245	867	**3.3**
20	542	901	143	1169	933	**3.3**

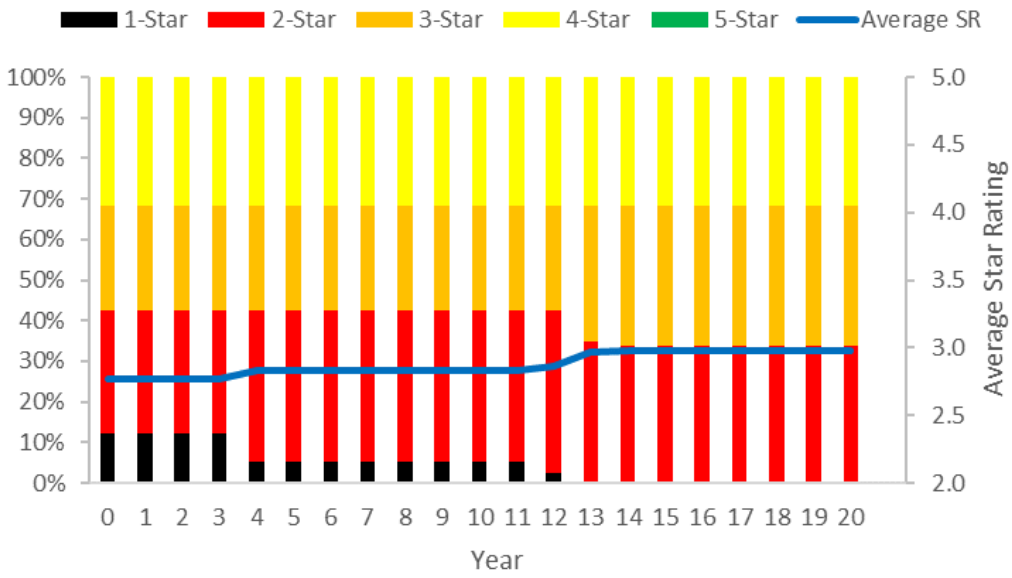
11.4 Base Scenario

11.4.1 Do Minimum

11.4.1.1 Countermeasure Effects (CE)

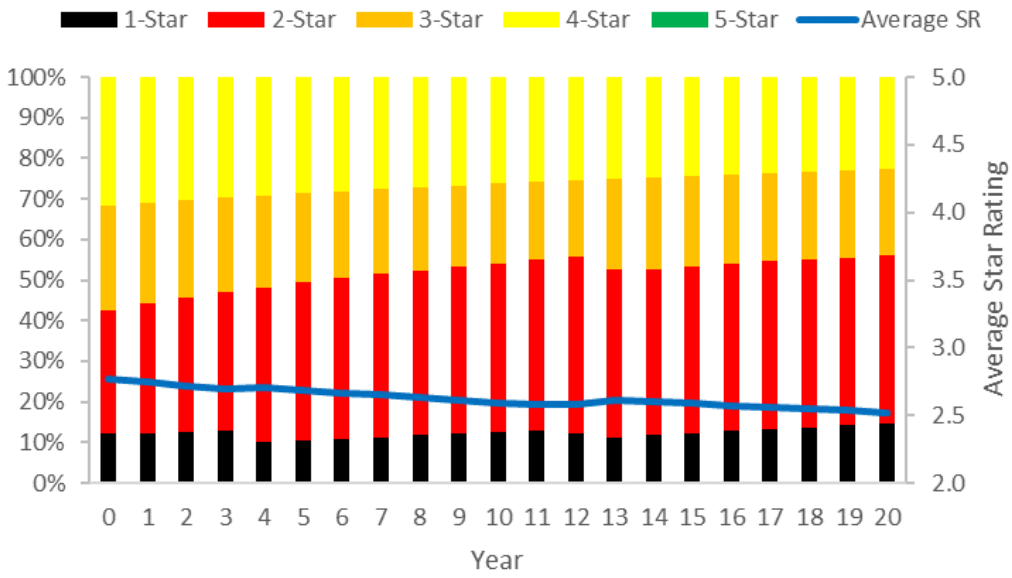
Year	Countermeasure Effects					Total
	Development C1	Upgrading 1 C2	Upgrading 2 C3	Periodic C4	Routine C5	
0	0	0	0	0	0	**0**
1	0	0	0	0	0	**0**
2	0	0	0	0	0	**0**
3	0	0	0	0	0	**0**
4	0	0	0	246	0	**246**
5	0	0	0	0	0	**0**
6	0	0	0	0	0	**0**
7	0	0	0	0	0	**0**
8	0	0	0	0	0	**0**
9	0	0	0	0	0	**0**
10	0	0	0	0	0	**0**
11	0	0	0	0	0	**0**
12	0	0	0	110	0	**110**
13	0	0	0	290	0	**290**
14	0	0	0	30	0	**30**
15	0	0	0	0	0	**0**
16	0	0	0	0	0	**0**
17	0	0	0	0	0	**0**
18	0	0	0	5	0	**5**
19	0	0	0	0	0	**0**
20	0	0	0	0	0	**0**

11.4.1.2 Annual Countermeasure Effects Deviation ($dRSR_{CE}$)



Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	444	1127	953	1163	1	**2.8**
2	444	1127	953	1163	1	**2.8**
3	444	1127	953	1163	1	**2.8**
4	198	1373	953	1163	1	**2.8**
5	198	1373	953	1163	1	**2.8**
6	198	1373	953	1163	1	**2.8**
7	198	1373	953	1163	1	**2.8**
8	198	1373	953	1163	1	**2.8**
9	198	1373	953	1163	1	**2.8**
10	198	1373	953	1163	1	**2.8**
11	198	1373	953	1163	1	**2.8**
12	88	1483	953	1163	1	**2.9**
13	0	1281	1243	1163	1	**3.0**
14	0	1251	1273	1163	1	**3.0**
15	0	1251	1273	1163	1	**3.0**
16	0	1251	1273	1163	1	**3.0**
17	0	1251	1273	1163	1	**3.0**
18	0	1246	1278	1163	1	**3.0**
19	0	1246	1278	1163	1	**3.0**
20	0	1246	1278	1163	1	**3.0**

11.4.1.3 Annual Road Safety Rating (RSR_{n+1})



Years	★	★★	★★★	★★★★	★★★★★	Average SR
0	444	1127	953	1163	1	**2.8**
1	455	1173	919	1140	1	**2.7**
2	467	1214	888	1117	1	**2.7**
3	480	1250	860	1096	1	**2.7**
4	371	1406	835	1075	1	**2.7**
5	386	1434	812	1056	1	**2.7**
6	401	1459	790	1037	1	**2.7**
7	416	1482	771	1019	1	**2.6**
8	432	1501	753	1001	1	**2.6**
9	448	1518	737	984	1	**2.6**
10	465	1533	722	968	1	**2.6**
11	482	1545	708	953	1	**2.6**
12	444	1611	695	938	1	**2.6**
13	417	1518	828	924	1	**2.6**
14	435	1511	832	910	1	**2.6**
15	453	1516	821	897	1	**2.6**
16	470	1521	812	884	1	**2.6**
17	488	1524	803	872	1	**2.6**
18	506	1523	797	861	1	**2.5**
19	524	1524	789	849	1	**2.5**
20	542	1524	782	839	1	**2.5**

Appendix 12 Research Publications, Presentations and Award

Two papers were presented related to this research as follows:

i. Azmi, A.E., Evdorides, H. 2017. Maintenance Programmes to Manage High-Risk Roads. XV. European Transport Congress & X. International Road Congress. European Platform of Transport Sciences (EPTS). Budapest, Hungary.

ii. Azmi, A.E., Evdorides, H. 2019. Life-Cycle Safety Rating of Road Maintenance Works. Proceedings of the 7th International Conference 'Bituminous Mixtures and Pavements' (7ICONFBMP). Thessaloniki, Greece. DOI: 10.1201/9781351063265-91.

During the academic year, this research has also participated in several activities and was awarded as follows:

i. Winner for the College of Engineering and Physical Science at the University of Birmingham Research Poster Conference 2017 on 15 June 2017.

ii. Runner-Up at the University of Birmingham Image of Research 2018.

EUROPEAN PLATFORM OF TRANSPORT SCIENCES (EPTS)

KÖZLEKEDÉSTUDOMÁNYI EGYESÜLET

2017. JUNE 8-9.

XV. Európai Közlekedési Kongresszus

X. Budapesti Nemzetközi Útügyi Kongresszus

Budapest, 2017. június 8-9.

TENT-T 25 ÉV
ÉPÍTÉS
FEJLESZTÉS
ÜZEMELTETÉS







BIZTONSÁGI ÉS
KÖRNYEZETVÉDELMI
KÉRDÉSEK



Traffic safety and environmental issues - ITS



Finance and project development



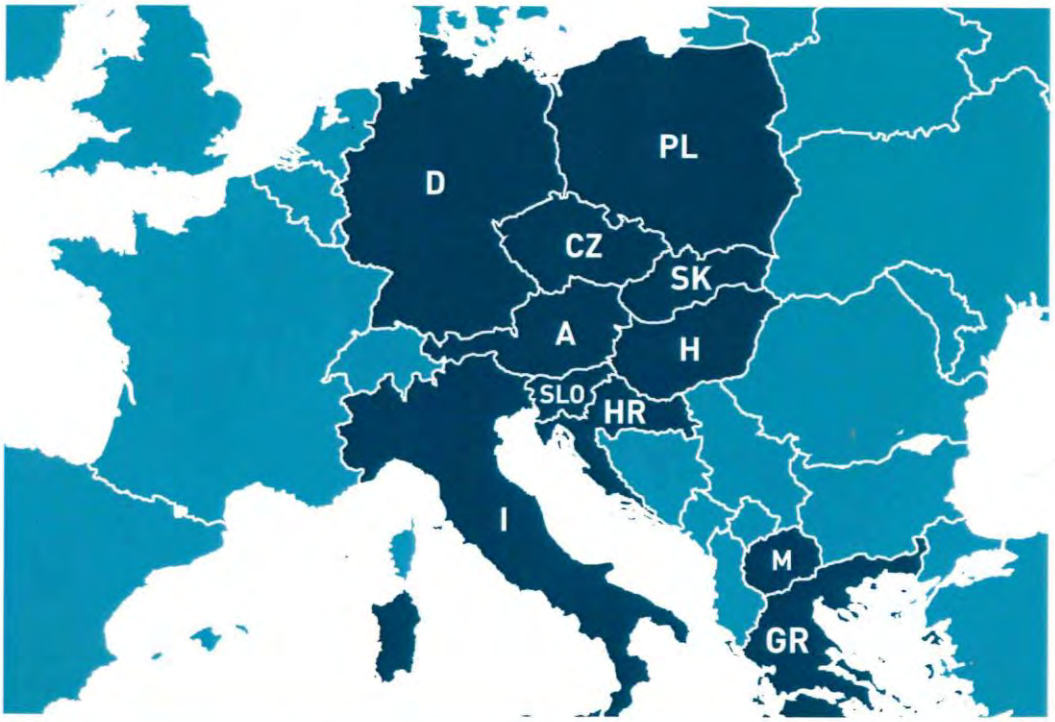




Hálózatfejlesztés, karbantartás, üzemeltetés







XV. EUROPEAN TRANSPORT CONGRESS

X. Budapest International Road Congress

XV. ETC and
X. BIRC

CONFERENCE PAPER

Maintenance Programmes to Manage High-Risk Roads

Azwan Ezzany Azmi [1], Dr. Harry Evdorides [2]

Abstract

One of the road maintenance objectives is to ensure safety for all road users whilst extending the life-cycle of the assets. With the emphasis on the life-cycle of the assets, road maintenance programmes are normally based on road pavement condition. Thus, there is a need to implement road maintenance programme based on safety. Currently, a road safety programme is used to identify high-return countermeasures in order to eliminate high-risk roads. However, the proposed countermeasures are treated as additional projects rather than being parts of a road maintenance programme. The objective of this study is to propose a road maintenance planning framework based on road safety scores. This study will analyse the changes in safety standard due to different road maintenance strategies and budget allocation. The result of this study will help to identify the compatibility for potential integration between available road safety models and road maintenance models.

Keywords

Road safety, road maintenance, management, planning, life-cycle analysis

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1 Introduction

International Road Assessment Programme (iRAP) is a systematic road inspection methodology that aims to measure the road safety risk consistently. Since the inception implementation of road assessment programme in 2004, there are more than 500,000 kilometres of roads have been systematically inspected involving 65 countries (iRAP, 2015). The countries that have taken part in the assessment are consist of all groups of income from low to high-income countries.

There are many pieces of evidences that show the benefits of iRAP where it was successfully implemented in some developed countries such as United Kingdom (Road Safety Foundation, 2016) and Australia. These were reflected either through a better road safety rating or through the reduction in accident or fatality and serious injury rates.

However, in some developing countries, there is no significant impact of iRAP inspections especially when the implementation of proposed investment are not carried out according to the plans. One of the reasons contribute to this problem is lack of funding to implement the whole investment plan. Clearly, some of these countries are also struggling to fund their road management and maintenance programme hence the road safety programme may also be ignored.

The objective of this paper is to demonstrate the possibility of integrating road maintenance and road safety programme in order to tackle both maintenance and road safety issues with optimum budget. Currently, road maintenance and road safety programme are carried out based on two different appraisal system. Two of the most widely used system for managing road maintenance and road safety are Highway Development Management Tools (HDM-4) and International Road Assessment Programme (iRAP) respectively.

This paper will enhance the methodology used in iRAP to establish a road maintenance programme that helps to manage high-risk roads. This road maintenance programme will be generated from the iRAP's Safer Road Investment Plan (SRIP) with the analysis will be done according to strategic planning of road decision-support system (Robinson, 2008).

2 Methodology

The methodology used in established iRAP protocol is consists of four processes namely Risk Maps, Star Ratings, Safer Road Investment Plan (SRIP) and Performance Tracking (Fig. 1). This paper will review the most significance processes in iRAP protocol, which are the Star Rating and the SRIP. Star Rating is used as a measure of road safety level of a road section that has been assessed based on iRAP methodology. The rating used in iRAP is between 1-star to 5-star which the lowest relates to the lowest safety features while the highest is vice-versa. SRIP is the countermeasures options proposed by iRAP system in order to enhance the Star Rating.

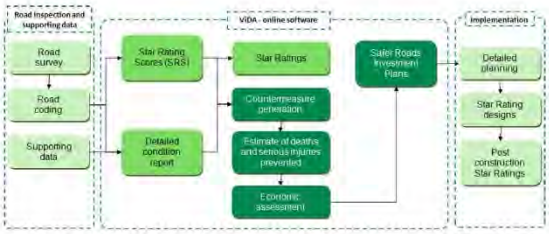


Fig. 1 The iRAP Star Rating and Safer Roads Investment Plan process (source: iRAP, 2014)

The current iRAP model of Version 3 generated the investment plan based on an economic assessment. The assessment is derived from accident cost which refers to the Value of Fatality as shown below (iRAP, 2015):

The economic benefit =
(Number of fatalities prevented x 70 x GDP per capita)
+ (Number of serious injuries prevented x 0.25 x 70 x GDP per capita) (1)

On the other hand, this paper will present an alternative method to reprioritise proposed SRIP based on different budget level. The proposed SRIP is categorised based on nature of work such as Routine Maintenance, Periodic Maintenance, Upgrading Work and Development Work. These work standards will be analysed in Star Rating Demonstrator to identify the work effects.

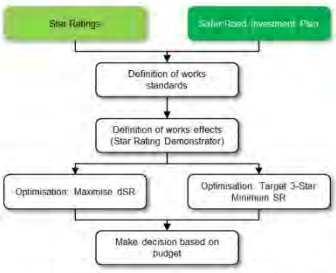


Fig. 2 The methodology framework used in this study

Newly defined SRIP will be analysed using treatment-based method adopted from Transport Research Laboratory (Robinson et. al., 2008). This analysis will evaluate the work effects to the Star Rating changes based on different budget level. The methodology framework used in this study is shown in Fig. 2.

3 Case Study

This study is based on 3,688 kilometre of Expressway (toll motorway) and Federal Road (primary road) in Peninsular Malaysia that represent the strategic road from the road network. Twelve stretches of roads are selected to represent this with the traffic category as Table 1 and the Star Rating as Table 2. In this study, only Car Occupants Star Rating is considered to simplify this initial trial analysis.

Table 1 Distribution of AADT by traffic category

Traffic Category	Traffic Range	Total Length	Average AADT
T1	> 25 000	1066 km	35 000
T2	10 000 – 25 000	2150 km	12 000
T3	< 10 000	472 km	5 000

Table 2 Star Rating (Car Occupants)

Star Rating	Length (km)	Percentage
★★★★★	1	0.03%
★★★★	1163	31.53%
★★★	953	25.84%
★★	1127	30.56%
★	444	12.04%
Total	**3688**	**100%**

From these three categories of traffic and five road safety condition ratings, the selected network is broken down into 15 conceptual sections which represent the road safety condition of similar attributes and require the same set of maintenance standard to be implemented. A Strategy Analysis (Network Level Analysis) will be performed to identify works priority. As a first generation prioritisation method, a treatment-based method has been adopted as suggested by Robinson et. al. (1998). The matrix of this approach is shown in Table 3.

Table 3 Works priority within the matrix of treatment-based method with relative to traffic hierarchy

Hierarchy of Maintenance Works	Works Category	Traffic Hierarchy		
		T1	T2	T3
P1	Periodic	*1*	*2*	*3*
R2	Routine / Cyclic	*4*	*5*	*6*
R1	Routine / Cyclic	*7*	*8*	*9*
P2	Periodic	*10*	*11*	*12*
U1	Upgrading	*13*	*14*	*15*
U2	Upgrading	*16*	*17*	*18*
D1	Development	*19*	*20*	*21*
R3	Routine / Cyclic	*22*	*26*	*30*
P3	Periodic	*23*	*27*	*31*
R4	Routine / Cyclic	*24*	*28*	*32*
R5	Routine / Cyclic	*25*	*29*	*33*

Table 4 Work standards and work effects used in the analysis based on Star Rating Investment Plan countermeasures

*Star Rating Investment Plan (SRIP) (Countermeasure Types)	*Length or number of sites	*Estimated Cost to Build and Maintain (20 years) MYR 'mil	*Programme Benefit-Cost Ratio	Work Standards	Work Effects	Remarks
Roadside safety - hazard removal	1650 km	24	121	Routine	R1/R2/R3/R4/R5	
Realignment - horizontal	3 km	1	117	Upgrading	U1	
Intersection - roundabout	20 sites	0.3	39	Periodic	P1	
Central hatching	10 km	0.4	36	Periodic	P1	
Intersection - right turn provision (signalised site)	60 sites	4	16	Periodic	P3	
**Motorcycle lanes	270 km	0 (17)	15	Development	D1	**Motorcyclist
**Bicycle facilities on or off road	0.7 km	0 (0.03)	15	Development	D1	**Bicyclist
Additional lane	380 km	179	14	Development	D1	
Intersection - right turn provision (unsignalised site)	120 sites	14	14	Periodic	P1	
Intersection - signalise	190 sites	25	13	Upgrading	U1	
Shoulder widening	270 km	34	12	Periodic	P1	
Median barrier	40 km	20	12	Upgrading	U1	
Improve delineation	130 km	11	12	Periodic	P1	
Road surface upgrade	10 km	0.8	11	Periodic	P3	
Duplication (additional lanes)	120 km	220	10	Development	D1	
Roadside safety - barriers	30 km	9	10	Periodic	P1	
Lane widening	30 km	6	9	Periodic	P1	
**Pedestrian crossing	130 sites	0 (13)	8	Development	D1	**Pedestrian
**Pedestrian footpath	10 km	0 (2)	7	Development	D1	**Pedestrian
Rumble strip / flexi-post	10 km	0.5	7	Periodic	P2	
Regulate roadside commercial activity	0.2 km	0.03	7	Periodic	P2	
Parking improvements	0.1 km	0.02	7	Periodic	P2	
TOTAL		**549.05 **(581.08)**	**16**			

**From iRAP output*
***Motorcyclist, Bicyclist and Pedestrian are not considered in this study*
(€1.00 = MYR4.70)

Table 5 Distribution of Star Rating (Car Occupants)

Route Number / Road Name	Traffic	Approximate Length (km)	%	Star Rating (km)				
				★	★★	★★★	★★★★	★★★★★
E1 Kuala Lumpur – Bukit Kayu Hitam	40000	495	13.42			80	415	
E2 Johor Bahru – Kuala Lumpur	35000	335	9.08			62	273	
E8 Karak - Kuantan	30000	236	6.40	5		5	225	1
Total Traffic T1	**105000**	**1066**	**28.90**	**5**	**0**	**147**	**913**	**1**
F1 Alor Setar – Kuala Lumpur	15000	459	12.45	30	270	110	49	
F3 Rantau Panjang – Johor Bahru	15000	725	19.66	59	324	292	50	
F2 Gebeng - Karak	10000	208	5.64	60	70	60	18	
F5 Johor Bahru - Ipoh	10000	680	18.44	70	270	240	100	
F7 Padang Besar – Alor Setar	10000	78	2.11	15	58	5		
Total Traffic T2	**60000**	**2150**	**58.30**	**234**	**992**	**707**	**217**	**0**
F4 Gerik – Kota Bahru	7000	200	5.42	100	70	30		
F8 Bentong – Sungai Temau	7000	163	4.42	50	20	60	33	
F67 Sungai Petani - Baling	3000	55	1.49	30	20	5		
F76 Baling - Gerik	3000	54	1.46	25	25	4		
Total Traffic T3	**20000**	**472**	**12.80**	**205**	**135**	**99**	**33**	**0**
TOTAL		**3688**	**100.00**	**444**	**1127**	**953**	**1163**	**1**

Table 4 shows the list of countermeasures proposed by iRAP's analysis using Vida Online (https://vida.irap.org/en-gb/home). This list of 22 countermeasures is outlined as Star Rating Investment Plan. They are prioritised based on Benefit-Cost Ratio that has been derived from Eq. (1). The countermeasures are consist of four occupants namely Car Occupants, Motorcyclist, Bicyclist and Pedestrian. However, this study will only consider 18 countermeasures related to Car Occupants in

the analysis. Table 5 shows the distribution of Star Rating on the selected network of 3,688 kilometre based on traffic characteristic.

The configuration of work effects has been analysed from Star Rating Demonstrator (https://vida.irap.org/en-gb /demonstrator). Each of the changes to road attributes due to countermeasure effects is simulated using this demonstrator to define the significant work effects in term of Star Rating. In general, the work effects can be rationalised as the following diagram where the priority of works are descending to the right of the order (Fig. 3).

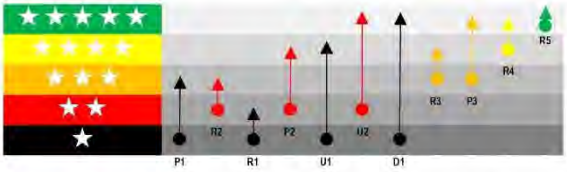


Fig. 3 The work effects as generated from the demonstrator

In this study, the requirement of the unconstrained budget in total of MYR549 million (€115 million) from the proposed Star Rating Investment Plan are spread out within 20-years budget year analysis. This has given an average amount of MYR30 million (± MYR5 million) assumed to be spent each year (Fig. 4). Four different budget strategies have been investigated as below:

a) Average budgeting: Each countermeasure is spread out within 20-years budget year analysis where the small scale countermeasures are allocated at appropriate year;
b) Benefit-Cost Ratio prioritised budgeting: Each countermeasure is allocated based on benefit-cost ratio prioritisation provided from iRAP output at an approximate average yearly cost within 20-years budget year analysis;
c) Treatment-Based budgeting: Each countermeasure is allocated based on treatment-based prioritisation at an approximate average yearly cost within 20-years budget year analysis;
d) Treatment-Based budgeting (with traffic): Each countermeasure is allocated based on treatment-based prioritisation and traffic characteristic at an approximate average yearly cost within 20-years budget year analysis.

The reason for selection of these four budget scenarios is to analyse the implication of applying different strategies on road works sequence, budget level and prioritisation method to road safety level. With this analysis, we will develop further the knowledge on how road works may affect road safety level. In another way, the provision of capital and recurrent budget within current financing mechanism can be optimised to implement road safety programme within road development and management programme.

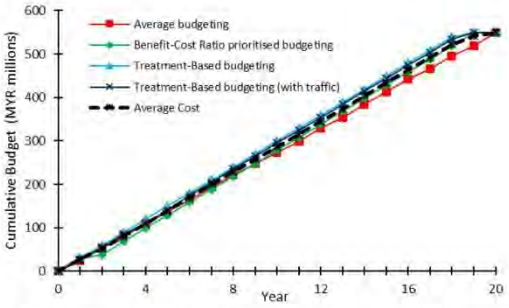


Fig. 4 Cumulative budget for four strategies of unconstrained budget scenario within the same range

In the analysis, each length of countermeasures is assumed to be affecting the same length of target roads. Similarly, all the countermeasures that have been proposed as a number of sites are assumed to be affecting a kilometre of road which they represent i.e. 20 sites may represent 20 kilometre of roads. It is also assumed that each work effect will react on the next safety rating if the designated rating has been cleared. For example, if 1-star road has been cleared, the proposed countermeasure D1 will react on the next star rating, which is on 2-star roads. The work effects from the implementation of the countermeasures based on four different budget scenario strategies are shown in Fig. 5 to Fig. 8 respectively.

3.1 Average budgeting strategy

The average budgeting strategy can be considered as the control measure of this analysis as all the countermeasures are spread out within 20-years budget year analysis. As the cumulative cost increased proportionally, the safety level of the network also increased proportionally. The 1-star roads are successfully eliminated after Year-3. However, there are remaining 5.93% of 2-star roads at the end of the 20-years analysis. With this budget scenario, the network reaches 70% of minimum 3-star roads on Year-5.

3.2 Benefit-Cost Ratio prioritised budgeting strategy

This budgeting strategy is done based on iRAP Star Rating Investment Plan (SRIP). The selected countermeasures are prioritised based on Benefit-Cost Ratio where the economic benefit is derived from Eq. (1). The 1-star roads are successfully eliminated after Year-1. However, there are remaining 5.90% of 2-star roads at the end of the 20-years analysis. With this budget scenario, the network reaches 70% of minimum 3-star roads on Year-8.

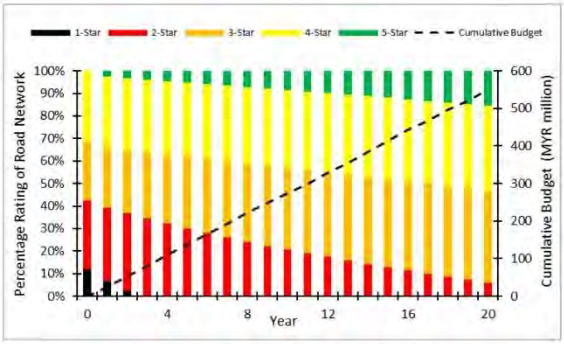


Fig. 5 Road works effect based on Average budgeting strategy

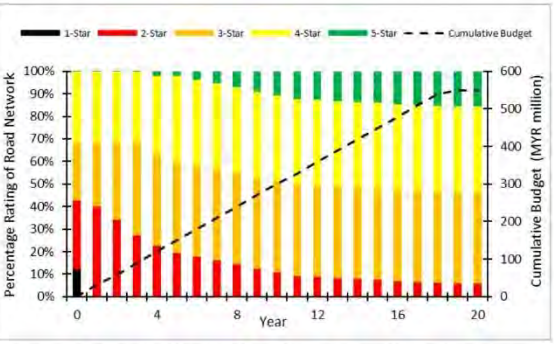


Fig. 7 Road works effect based on Treatment-Based budgeting strategy

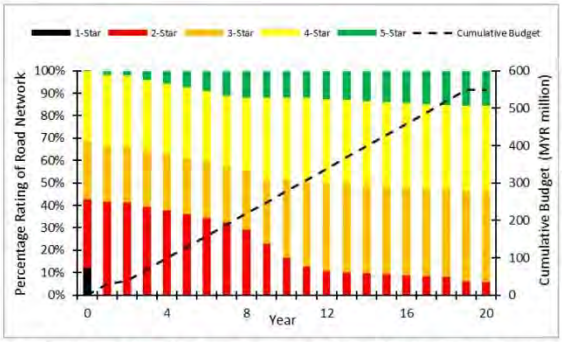


Fig. 6 Road works effect based on Benefit-Cost Ratio prioritised Budgeting strategy

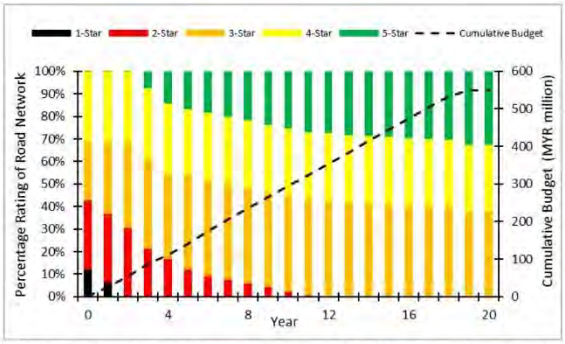


Fig. 8 Road works effect based on Treatment-Based budgeting strategy (with traffic)

3.3 Treatment-Based budgeting strategy

The objective of Treatment-Based budgeting strategy is to maximise the 3-star and above roads by eliminating the 1-star and 2-star roads. At the early stage of analysis, countermeasures are implemented on the 1-star and 2-star roads to increase the safety level by a minimum of 3-star. The 1-star roads are successfully eliminated after Year-1. However, there are remaining 5.90% of 2-star roads at the end of the 20-years analysis. With this budget scenario, the network reaches 70% of minimum 3-star roads on Year-3.

3.4 Treatment-Based budgeting strategy (with traffic)

In this analysis, the Treatment-Based budgeting strategy is improvised to investigate the effect of road safety level when the traffic element is considered in the implementation strategy. The priority is based on the treatment-based matrix as shown in Table 3. The 1-star roads are successfully eliminated after Year-2 while the 2-star roads are successfully eliminated after Year-11. With this budget scenario, the network reaches 70% of minimum 3-star roads on Year-3.

4 Discussion

The implementation of countermeasures in the Average budgeting strategy is not prioritised. This budgeting strategy is implemented when there is no basis for technical appraisal. The aim of strategy in term of road safety target is unclear and the purpose is only to distribute the budget.

From Fig. 6, we can suggest that the prioritisation method used in Star Rating Investment Plan (SRIP) considers more on economic parameters rather than technical parameters. As the Benefit-Cost Ratio which has been considered in the analysis is based on the value of the economic benefit from Eq. (1), the prioritised countermeasures reacted by increasing star rating on every level. In this way, more 2-star roads are created while the increase in 3-star and above is insignificant on the early stage of analysis years. Significant increment on 3-star and above appears only on Year-9 to Year-12 where more appropriate countermeasures affecting the strategic roads thus increasing the safety rating of these roads.

Fig. 7 shows that significant changes to the 3-star roads from Year-1 when the Treatment-Based budgeting strategy is implemented. This can be achieved when the prioritisation of countermeasures considers the work effects to the safety rating. The aim of this strategy is to maximise the 3-star and above roads by implementing appropriate countermeasures based on their

significant work effects as presented in Fig. 3.

An improved concept is applied to the fourth strategy where traffic hierarchy has been included as the prioritisation factor in the Treatment-Based budget strategy. It is shown in Fig. 8 that significant impact can be seen with the implementation of this concept. The most significant impact of this strategy is it managed to achieve 70% target of 3-star and above roads within a short period of 3 years and reached 100% target after Year-11.

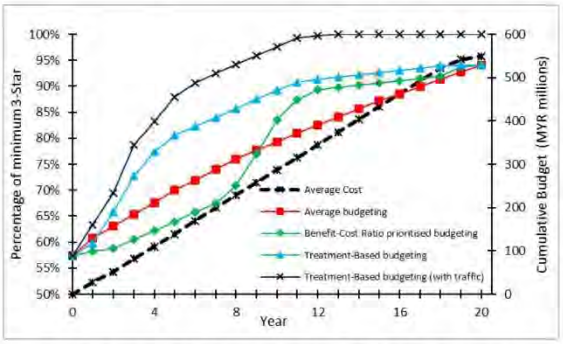


Fig. 9 Percentage of minimum 3-star roads for each budget scenario

Fig. 9 clearly shows the effects of all four budget scenario with regards to percentage of 3-star and above network. For Average budgeting, the percentage increase proportionately. For Benefit-Cost Ratio prioritised budgeting, the increment rate is lower than average in the beginning but it picks up well in the middle of the analysis year. The Treatment-Based budgeting shows a clear evidence of how different strategy may provide many options during the implementation of road safety programmes. Nevertheless, applying different traffic hierarchy to this strategy may suggest that traffic is another strategic parameters that need to be explored in this model. If there is a budget shortage, Fig. 9 can be used to determine the network safety condition at certain budget cut-off based on different budget strategy.

Previous study by Khan et. al. (2016) and Tighe et. al. (2000) and report from Mahoney et. al. (2006) on the potential of incorporating road safety into maintenance activities have stressed how pavement surface properties such as friction, surface texture, roughness, distress and properties of paving materials affecting accident rate in adverse weather conditions. Tighe et. al. and Mahoney et. al. however supported the view that other road maintenance related to pavement works such as geometric design or cross-sectional features, road marking, signing, and visibility of pavements contribute to road safety enhancement. The methodology and results from this study may provide evidences to support this statement. For example, "Road surface upgrade" has been assigned as P3 work effect where it can increase the safety level from 3-star to 5-star which is not substantial in removing high-risk roads. Other prominent countermeasures such as "Realignment – horizontal" which has been assigned with U1, "Central hatching" (P1), "Additional lane" (D1), "Intersection – signalise" (U1), "Improve delineation" (P1), "Shoulder widening" (P1), "Duplication (additional lanes)" (D1), "Lane widening" (P1), "Rumble strip / flexi-post" (P2) and "Parking improvements" (P2) are more significant in reducing high-risk roads thus need to be prioritised.

Based on these results and characteristics, we assumed the methodology that has been presented in this study is applicable in providing a first generation decision-support system for road safety investment appraisal. This model is based on assumption that individual countermeasure is applied on 1 kilometre of road segment. Further investigations need to be done to apply multiple countermeasures on a road segment and develop further this model into second and third generation decision-support system.

5 Conclusions

As a first generation decision-support system for road safety investment appraisal, this study is not intended to identify the best strategy to implement road safety programme. Even though the results show that the Treatment-Based budgeting (with traffic) performed well better than the other budgeting strategy, it is not necessary to justify that certain strategy is better than others. This study may provide a forecast on how the road safety condition of a network when subject to a certain budget scenario.

Currently, the existing available road safety investment appraisal system could only propose an investment plan for implementation. That system could not assess the average road safety condition with regards to certain budget constraint. This study successfully demonstrated the methodology on how to identify the average road safety condition with regards to different budget strategy and budget constraint.

As for road management and maintenance, a number of systems are available to analyse this such as Highway Development and Management Tools (HDM-4) and Road Network Evaluation Tools (RONET). These systems are the advanced third generation decision-support system which basically operated with the same concept. In order to explore the compatibility for potential integration between available road safety models and road maintenance models, this study has reduced the gap between both maintenance and road safety appraisal tools by this methodology.

In future, this model can be integrated into HDM-4 or RONET as a complete decision support tools. To prepare this, further investigations need to be done in order to develop the first generation model into second generation and third generation decision-support system. For the second generation, further researches need to be done to understand the future consequences of countermeasures during their life-cycle to include in the model. Further research to complete this model as the third generation need also to be done by looking into an advances economic analysis.

Acknowledgement

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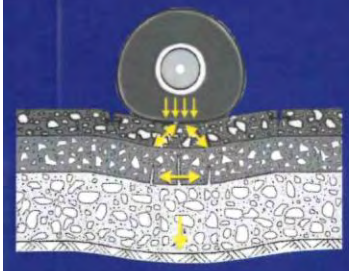
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Life-Cycle Safety Rating of Road Maintenance Works

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ABSTRACT: About 1.25 million death reported each year as the result of road traffic accidents. This is often associated with the lack of road management fund. Several decision support tools are available to be used to help in providing solution as a good road maintenance management practice. This paper discusses the application of road maintenance strategies which coupled with road safety condition in order to manage high-risk roads. The objective of this study is to identify the effect of road maintenance works and road safety countermeasures to road safety condition. The study analyses the effects of road assets deterioration and road maintenance strategies to road safety condition as a performance monitoring to a long-term planning at network level. From the analysis, it can be concluded that the analytical framework and modelling concept proposed in this study have successfully demonstrated the method to identify road maintenance works and road safety countermeasures effects to road safety condition.

1 INTRODUCTION

1.1 *Background*

In 2015, the World Health Organisation (WHO) highlighted that about 1.25 million death reported each year as the result of road traffic accidents. Moreover, 90% of these fatality rates are contributed by the road accident that occurred in low and middle-income countries (LMIC). This alarming statement is often associated with the fact that these countries are lack of road management fund especially for the works related to road safety countermeasures besides the rehabilitation works (WHO 2015).

Lack of road maintenance fund is a general problem that has been faced by many road administrators for years. Limitation of this fund has urged the road managers to spend the allocation wisely to avoid unnecessary roadworks which contribute inefficiency to the road operations and more inconvenient to the road users. Several decision support tools are available to be used by managers to help in providing solution and alternatives as a good road maintenance management practice such as the highly considered Highway Development and Management Tools (HDM-4). It is up to the manager to choose the most appropriate decision support tool that best helps in decision making where they better satisfy the needs of road users (OECD 1994).

In general, a common philosophy of decision support tools for road management will need to consider the cycle within the road maintenance management function. The process of maintenance management for road networks generally consists of strategic planning, programming, preparation and operation. For each of this process, the concept of the management cycle is used as a common system for decision making (Kerali, Odoki & Stannard 2000).

Road maintenance management is an essential need to ensure a sustainable road network that contributes to the development of a sustainable society. The application of road maintenance management is highly influenced by the availability of budget. Without a proper maintenance management strategy, we may find out that some road organisations choose to prepare their budget for road maintenance in a traditional way based on historical allocation with some adjustment to the previous budget (Robinson 2008).

The requirement of budget can be categorised into six strategic targets namely physical condition, safety parameters, asset sustainability, network operational, budget execution, environmental and stakeholders interest (Weninger-Vycudil et al. 2016). Currently, there are not many of the available decision support tools that consider multiple-criteria in their analytical frameworks. It has always been envisaged that there will be an advanced decision support tools that may help road managers in considering budgetary needs of cross assets and multiple strategic targets.

Even though there are many established tools available for practical use, the effort to develop and enhance them need to be done continuously as those systems mostly considered the pavement condition

rather than other assets and strategic targets. Hence, there is a need to develop such tools that consider multiple-criteria and also other strategic targets such as road safety parameters and physical condition to address high-risk roads together with other maintenance management issues.

1.2 *Objectives*

This paper discusses the application of road maintenance strategies which coupled with road safety condition in order to manage high-risk roads. High-risks roads are defined by Federal Highway Administration (FHWA) as "any roadway with significant safety risks" (Atkinson et al. 2014). In the context of this paper, the safety risks can be considered from a historical accident data or based on certain road safety assessment.

The objective of this study is to identify the effect of road maintenance works and road safety countermeasures to road safety condition. The study analyses the effects of road assets deterioration and road maintenance strategies to road safety condition as a performance monitoring to a long-term planning at network level. The overall aim of the research is to establish the methodology for integration of road safety and road maintenance as a total road asset management appraisal that tackles both road maintenance and road safety issues. This will probably reflect the real effects of road maintenance management implementation and strategy on road safety condition that has rarely been assessed.

2 LITERATURE STUDY

2.1 *Integration of Road Safety and Road Maintenance*

The main objective of road maintenance management is to reduce the total transport cost while extending the life-cycle of the asset in a safe environment. One of the benefits of road maintenance works has always been associated with significant safety effects. The number of studies that have evaluated the effects of road maintenance on road safety is considered high (Elvik et al. 2009). Most of these studies evaluated the effects of road surface such as friction, roughness, distress and pavement drop-off on road safety (Tighe et al. 2000, Noyce at al. 005 & Khan et al. 2016).

Considering the other road components and wide-ranging of road maintenance works, which not only limited to pavement, the number of studies that have evaluated the other roadworks or road components in term of safety effects are relatively very low (Elvik et al. 2009). The effects of other components such as street illumination, road marking, traffic signages and road safety features installation that can be included in the category of routine, periodic or special works under road maintenance should also be evaluated as they offer quite a significant impact to road safety. For maintenance management, this evaluation is not only for monitoring and review purposes but it also provides valuable information for decision-support.

2.2 *Road Safety Indicators*

In most cases, the implementation of road safety improvement programmes for high-risk roads is mostly carried out as a reactive measure rather than preventive due to limited budget. Although there are also some preventive measures, the percentage when compare to reactive is considered very low. The nature of these programmes is categorised as reactive because they are based on historically proven accident locations or also known as black-spot areas rather than proactive assessment such as road safety audit. This programme requires the analysis of available accident data for ranking and design purpose. However, the quality and quantity of the accident database is varied especially in developing countries where the accident record are ambiguous (Mikulik & Hollo 2007). Thus, it may reflect the quality and the effectiveness of the implemented road safety programme.

There are previous studies which also applied available accident data to predict the future accident rate. Numbers of accident prediction models have been developed by researchers to estimate the accident rate. These model are used for road safety evaluation purpose to evaluate the effectiveness of road safety countermeasure before and after the implementation as the indicator of safety effects. They also can be used as decision-support tools to compare several strategies in order to assess the effectiveness of different countermeasures (Elvik et al. 2009). Similarly, the accident prediction model approach such as crash modification factor (CMF) relies on the quality of the available accident data which may reflect the quality of the result (Lord & Bonneson 2006).

Researchers have concluded some different opinions regarding the parameter or indicator that should be used to evaluate road safety. Road safety index or indicator can be used to compare road safety performance between locality and country, assess road safety situation, benchmarking, propose countermeasure and as decision support for improvement programme. In general, the indicators of road safety can be categorised into three phases namely road user aspects, road environment aspects and accident aspects. The quality of road safety indicator depends largely on the selected parameters, weightage and data aggregation (Tešić et al. 2018). As synchronisation of data between countries is inconsistent, it is difficult to make an ideal comparison of road safety performance between countries. There are also possibilities that the inconsistent of data may occur locally. Therefore, it is vital that a standardised road safety index is used with all the parameters that are

applied to the index which can be gathered through systematic road survey or inspection.

2.3 *Star Rating Score (SRS)*

One of the currently established methodology to assess road safety condition by road survey or inspection is Star Rating protocol. Star Rating has been developed by the International Road Assessment Programme (iRAP) as a simple objective measure to assess the level of safety around the road environment where roads are being rated between 1-star to 5-star with 5-star is considered the safest road (iRAP 2009). Star Rating is calculated based on Star Rating Score (SRS) with the following equation (iRAP 2014):

$$SRS = \sum Crash\ Type\ Scores \quad (1)$$

$$Crash\ Type\ Scores = Likelihood\ x\ Severity\ x\ Operating\ speed\ x\ External\ flow\ influence\ x\ Median\ traversability \quad (2)$$

As shown in Equation 2, Star Rating Score is formulated without direct relation to accident data. This is an advantage of Star Rating Score when compares to the other road safety indicators as it could avoids any issue related to ambiguity of accident data, especially in low and middle income countries. Star Rating Score is a derivative function of road attributes which enable us to explain the condition of road environment in a simple indicator or rating band. With iRAP methodology, about 78 road attributes are recorded and decoded to establish the Star Rating Score and ultimately to identify the Star Rating of the assessed road. Further explanation about Star Rating Score and Equation 2 can be referred in iRAP (2014). Star Rating Score also can be acquired using Star Rating Demonstrator provided by iRAP at *https://demonstrator.vida.irap.org/calculate-star*. This demonstrator helps to calculate the Star Rating Score based on assigned road attributes.

There are not many established road asset management systems that have been used widely around the world. Contrariwise, Highway Development and Management Toolkit (HDM-4) is one of the available road asset management system which has been recognised by World Bank. It is widely used by developing and developed countries as a decision support tool for road maintenance and development investment appraisal.

Similarly, for road safety, International Road Assessment Programme (iRAP) has started to gain the trust by road managers around the world. It is reported that the iRAP methodology has been used in more than 65 countries to assess the road safety condition involving more than 500,000 kilometres of roads (Charman & McInerney 2009). As such, the iRAP methodology would be justified as one of the most advanced road safety management system currently available worldwide. For this study, the iRAP methodology of road safety ratings will be considered to be coupled in the application of road maintenance strategies to manage high-risk roads. Figure 1 shows the iRAP Star Rating methodology and Safer Roads Investment Plan (SRIP) process.

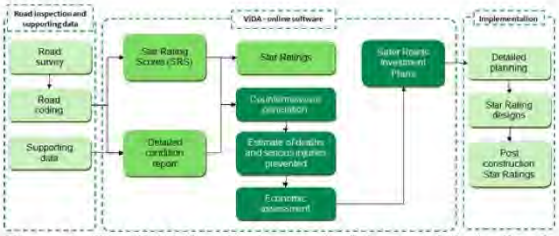


Figure 1. The iRAP Star Rating methodology and Safer Roads Investment Plan process (iRAP 2009).

3 THE ANALYTICAL FRAMEWORK AND MODELLING CONCEPT

The analytical framework used in pavement life-cycle analysis is the most appropriate method to generally model overall component of road assets. The rest of the road asset components such as slope, drainage system, road shoulder, signages, road furnitures et cetera are perhaps too small, small-percentage in scope and cost or last longer (if compared to pavement) so they can be assumed to be deteriorate at negligible rate. This concept will further be explained in 3.1. Fundamental knowledge of pavement life-cycle analysis has been applied to establish road safety life-cycle analysis. Figure 2 shows how the proposed analytical framework for road safety countermeasure life-cycle analysis used in this study.

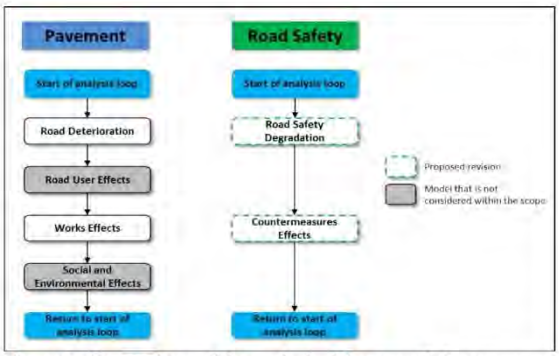


Figure 2. Comparison of the analytical framework for pavement (left) and road safety (right).

In the pavement life-cycle analysis, the cost components of Road Deterioration (RD), Road User Effects (RUE), Works Effects (WE) and Social and Environmental Effects (SEE) are analysed to determine the total transport cost as the economic analysis. For

the road safety life-cycle analysis, only the road safety rating or also known as Star Rating of Road Safety Degradation (RSD) and Countermeasure Effects (CE) is used to determine the road safety condition. The cost components and economic analysis in road safety analysis can be ignored as they can be determine as part of the pavement life-cycle cost analysis.

3.1 *Road Safety Degradation (RSD)*

The Star Rating Score has been derived from the summation of the Crash Type Score which depend on likelihood, severity, speed, flow and traversability of crash. From all the road attributes, only Road Condition (good, medium and poor) and Skid Resistance (adequate, medium and poor) are subject to deterioration. There are nine probabilities of combination between Road Condition and Skid Resistance that may reflect any changes to Star Rating marked with effects code E1 to E5 based on the extend of their severity. The combination in E1 effects are not sensitive to Star Rating Score which shows that road safety level do not degrade with slight deterioration when the quality of road is considered in good condition. The changes of Star Rating Score and Road Safety Degradation are illustrated in Figure 3.

The relationship between the variables involved in determining the Star Rating Score compared to the degradation model is not in the scope of this study. For the purposes of this study, a directly proportional relationship is assumed for the deterioration of the pavement. Relatively, 100% of failure will be experienced by the pavement within 20 years of the analysis period or 5% per annum. The relationship of pavement deterioration model and road safety degradation model is also not in the scope of this study. This degradation model is applied for the development of the road safety degradation model that consider the life-cycle of the asset.



*Note : *Skid Resistant : A-Adequate, B-Medium, C-Poor*
***Road Condition : A-Good, B-Medium, C-Poor*

Figure 3. Road Safety Degradation based on Road Condition and Skid Resistant road attribute.

3.2 *Countermeasure Effects (CE)*

The Star Rating Score as shown in Equation 1 and Equation 2 can be used to calculate the Star Rating of existing road and also forecast the Star Rating of the road after the implementation of road works. Considering the changes that a set of road works or countermeasures can effectively increase the road safety ratings, there are 11 probabilities of work effects or Countermeasure Effects that might occur as summarised in Figure 4. The Countermeasure Effects will be used in the analysis to predict the effect of road maintenance works to road safety.

Figure 4 shows the Countermeasure Effects resulted from maintenance works and road safety countermeasures which can be classified into four categories such as Routine Maintenance, Periodic Maintenance, Upgrading and Development. The Countermeasure Effects are used to reset the road safety rating on the implemented area. They are used to manage road safety target in order to implement road maintenance programme by different budget scenario (Azmi & Evdorides 2017).

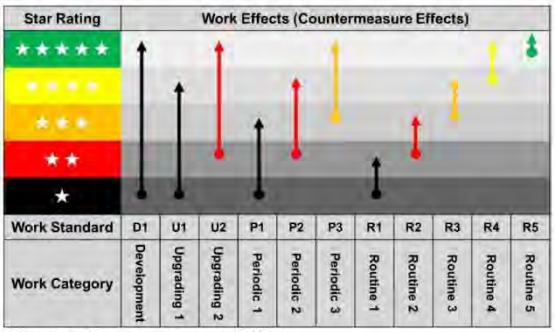


Figure 4. Countermeasure Effects.

3.3 *Case Study*

About 3688 kilometres of road which consists of Toll Expressway (motorway) and Federal Road (primary road) in Peninsular Malaysia has been chosen for this study. Table 1 shows the distribution of Star Rating for the selected road from the initial survey. Only Car Occupants has been considered for this study to simplify the analysis. In general, about 42.6% of road networks are in high-risk where they fall on 1-star and 2-star ratings.

Table 1. Star Rating (Car Occupants).

Star Rating	Length (km)	Percentage
★★★★★	1	0.03%
★★★★	1163	31.53%
★★★	953	25.84%
★★	1127	30.56%
★	444	12.04%
Total	**3688**	**100%**

The list of road maintenance works that have been considered for the chosen network is shown in Table 2. The maintenance standard applied in this analysis is based on average annual expenditure under the current Federal road maintenance contract in Malaysia. The road works that will be considered for analysis in this study are the Routine Maintenance and the Periodic Pavement Maintenance.

The other types of road works such as the Special Works, the Emergency Works and other type of Periodic Maintenance were not considered to clearly identify the effects of typical road maintenance to road safety. High-cost works which may require capital expenditure such as Upgrading and Development works are also not considered in this analysis.

Table 2. List of road maintenance works.

Countermeasure Type	Length of sites (per year)	Estimated Yearly Maintenance Cost / RM	Estimated Cost to Build and Maintain (20 years) / RM	Maintenance Type (Based on budget allocation)	Work Effects
Routine Maintenance					
• R01 - Patching / Sealing	37 km2	20 m	400 m	Routine	R1, R2, R3, R4, R5
• R02 - Regrading Road Shoulder	74 km	10 m	200 m	Routine	Minimum
• R03 - Grass cutting	NA	5 m	100 m	Routine	
• R04 - Road Furniture Cleaning	NA	5 m	100 m	Routine	Minimum
• R05 - Clearing Vegetation	NA	4 m	100 m	Routine	
• R06 - Roadline Repainting	1844 km	20 m	400 m	Routine	Minimum
• R07 - Drainage	NA	5 m	100 m	Routine	
		(69 m)	**(1400 m)**		
Periodic Maintenance (Pavement)					
• Overlay	120 km	24 m	480 m	Periodic	P1, P2, P3
• Mill & Replace	45 km	14 m	270 m	Periodic	P1, P2, P3
• Reconstruction	10 km	6 m	113 m	Periodic	P1, P2, P3
R02 - Regrading Road Shoulder	120 km	-	-	Periodic	Minimum
R06 - Roadline Repainting	175 km	-	-	Periodic	Minimum
		(44 m)	**(863 m)**		
Total		**113 m**	**2263 m**		

4 RESULT AND DISCUSSION

The analytical framework and modelling concept introduced in this study have provided a methodology to evaluate the effects of life-cycle deterioration and maintenance work on the road assets in term of road safety rating. The most important effects that are being studied are related to deterioration and road maintenance effects to road safety. Figure 5 shows the Road Safety Degradation due to life-cycle deterioration and Figure 6 shows the Countermeasure Effects from the implementation of road maintenance works.

4.1 *Road Deterioration Effects to Road Safety Ratings*

Taking into consideration the deterioration of the assumed rate at 5% per annum, the percentage of 4-star roads declined annually at an average rate of 16% until all the 4-star roads turn to 3-stars in the 15th year. The direct effect from declining 4-star roads has increased the percentage of 3-star roads at an average rate of 3% annually. It is because the 3-star roads also simultaneously degraded to the 2-star roads at the average rate of 5% per annum. The 3-star roads reached the highest percentage on the 16th year when all of the 4-star roads turned to 3-star. The 3-star roads gradually declined at an average rate of 8% towards the end of the analysis period.

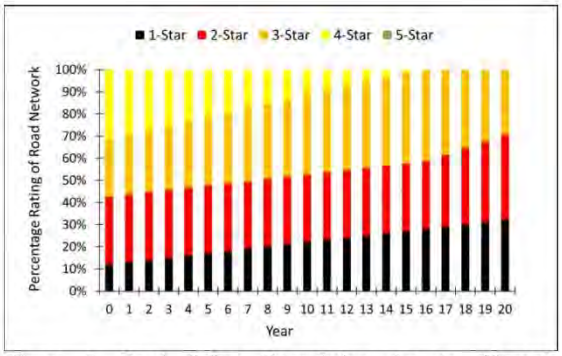


Figure 5. Road Safety Degradation due to life-cycle deterioration.

The percentage of 2-star roads unchanged from the beginning of the analysis until the 16th year. This is because the length of road networks that turned to the 2-star roads from the 3-star roads is equivalent to the

length of road networks that turned to the 1-star roads from the 2-star roads. However, the percentage of 2-star roads increased at an average rate of 6% towards the end of the analysis period from the 17th year contributed by the 3-star roads. Meanwhile, the percentage of 1-star roads increased at an average rate of 5% towards the end of the analysis period which mostly contributed by the 2-star roads.

4.2 *Road Maintenance Effects to Road Safety Ratings*

The maintenance works applied to this study is a typical road maintenance programme that comprise of Routine Maintenance and Periodic Maintenance as described in Table 2. The analysis is set as annual constant cost with constrained budget by 5% of total network length for Periodic Pavement Maintenance. These settings explained the result of analysis as shown in Figure 6 where the road safety ratings of 5-star roads increased constantly with the rise of cumulative budget.

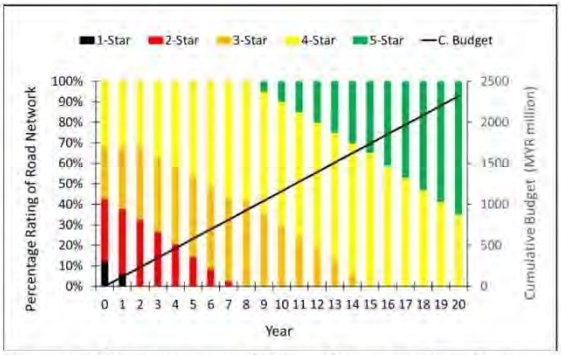


Figure 6. Countermeasure Effects due to road maintenance works.

The 1-star, 2-star and 3-star roads have been managed to be eliminated on the 2nd, 8th and 15th year of the analysis respectively. Towards the end of the 20-year analysis, all of the road networks are consist of 4-star and 5-star only. This has been achieved with only typical road maintenance works which resulted from R1, R2, R3, R4, R5, P1, P2 and P3 Countermeasure Effects as explained in Figure 4. However, this controlled condition is not reflecting the behaviour of road assets in reality. Therefore, we need to consider the life-cycle analysis of the road safety effects.

4.3 *Life-Cycle Analysis*

Life-cycle analysis has been carried out based on the deterioration model of Road Safety Degradation and Countermeasure Effects from the proposed road maintenance programme. For this analysis, the deterioration effects are applied first before the effect of maintenance is set. The result of this analysis is shown in Figure 7.

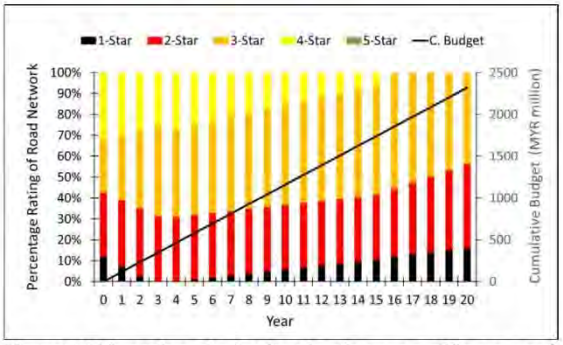


Figure 7. Life-cycle analysis of road maintenance effects on road safety.

Figure 7 can be explained in three phases namely early-stage (0-3 years), mid-stage (4-15 years) and end-stage (16-20 years). In the early stage, percentage of the 4-star roads and the 1-star roads are decreased where the 4-star roads declined because of degradation to the 3-star roads while 1-star roads turned to the 2-star roads. The 3-star roads increased as contributed by deterioration of the 4-star roads and maintenance effects from the 1-star roads. The 2-star roads remain constant throughout early-stage and mid-stage due to the equilibrium achieved from deterioration and road maintenance.

In the mid-stage, the percentage of the 1-star and 3-star roads increased constantly resulted from the deterioration of the 2-star roads and maintenance of the 1-star roads respectively. The 4-star roads declined constantly throughout the mid-stage until all of them turned to the 3-star roads. Towards the end of the analysis, there are only the 1-star, 2-star and 3-star roads remain. The rest of the 4-star and 5-star roads deteriorated to the lower safety ratings. Table 3 shows the comparison of Star Rating before and after the analysis.

Table 3. Percentage of Star Rating before and after the analysis.

Star Rating	Before		After	
	Length (km)	Percentage	Length (km)	Percentage
★★★★★	1	0.03%	-	-
★★★★	1163	31.53%	-	-
★★★	953	25.84%	1609	43.64%
★★	1127	30.56%	1489	40.36%
★	444	12.04%	590	16.00%
Total	**3688**	**100%**	**3688**	**100%**

5 CONCLUSION

This paper has discussed the life-cycle safety rating of road maintenance works. In the analysis, Star Rating Score (SRS) has been used to simulate the changes in road safety ratings due to road deterioration and road works or countermeasures effects. This analytical concept has been successfully presented with a case study to demonstrate the life-cycle safety rating of road maintenance works.

The road maintenance strategy that being used in this analysis has proven that typical road maintenance programme will only maintain minimum road safety level but will not increase it. Road maintenance alone is not sufficient to maintain the level of road safety. A road safety countermeasure strategies such as single site, mass action or area action need to be considered as a strategy for accident reduction and prevention. Upgrading works and development works needs to be implemented to improve road safety level to the minimum of 3-star roads as promoted by World Bank.

This study has achieved its objective by providing a methodology to identify the effect of road maintenance works and road safety countermeasures to road safety condition. From the analysis, it can be concluded that the analytical framework and modelling concept proposed in this study have successfully demonstrated the method to identify road maintenance works and road safety countermeasures effects to road safety condition. The study analyses the effects of road assets deterioration and road maintenance strategies to road safety condition as a performance monitoring to a long-term planning at a network level.

In future, this methodology can be used to analyse the road maintenance strategies to identify the most economic and beneficial investment in term of road safety. It is suggested that this study can be extend to analyse the effects of different type of road safety countermeasures and their life-cycle. Further improvement can be done to the road investment appraisal model by integrating road safety rating as one of the engineering assessment.

6 ACKNOWLEDGEMENT

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Maintenance programmes to manage high-risk roads

Azwan Ezzany Azmi* and Dr. Harry Evdorides / *aea199@student.bham.ac.uk

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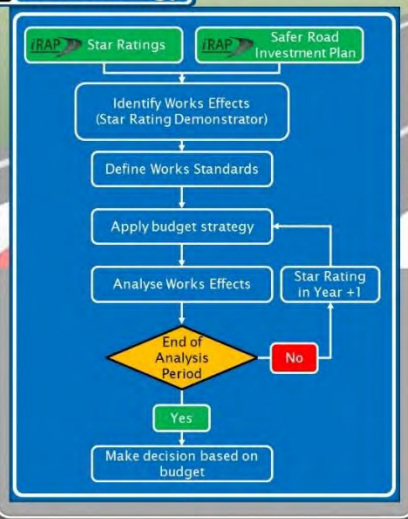
1 Introduction

- One of the **road maintenance** objectives is to ensure **safety for all road users** whilst **extending the life-cycle** of the assets.
- Road maintenance programmes are normally based on road pavement condition.
- Thus, there is a need to implement **road maintenance programme based on safety**.

2 Objectives

- This study will analyse the changes in safety standard due to different road maintenance strategies and budget allocation.
- The result of this study will help to identify the compatibility for potential **integration** between available **road safety models and road maintenance models**.

3 Methodology



Maintenance or Road Safety: Where should we spend our MON£Y?

4 Case Study



Figure 1 Location of pilot study in Peninsular Malaysia

Table 1 Star Rating of selected road network

Star Rating	Length (km)	Percentage
★★★★★	1	0.03%
★★★★	1163	31.53%
★★★	953	25.84%
★★	1127	30.56%
★	444	12.04%
Total	3688	100%

Table 2 Traffic classification of pilot study

Traffic Category	Traffic Range	Total Length	Average AADT
T1	> 25 000	1066 km	35 000
T2	10 000 – 25 000	2150 km	12 000
T3	< 10 000	472 km	5 000

5 Result & Conclusion

1. **Average budgeting**

Each countermeasure is spread out within 20-years budget year analysis where the small scale countermeasures are allocated at appropriate year.

2. **Benefit-Cost Ratio prioritised budgeting**

Each countermeasure is allocated based on benefit-cost ratio prioritisation provided from iRAP output at an approximate average yearly cost within 20-years budget year analysis.

3. **Treatment-Based budgeting**

Each countermeasure is allocated based on treatment-based prioritisation at an approximate average yearly cost within 20-years budget year analysis.

4. **Treatment-Based budgeting (with traffic)**

Each countermeasure is allocated based on treatment-based prioritisation and traffic characteristic at an approximate average yearly cost within 20-years budget year analysis.

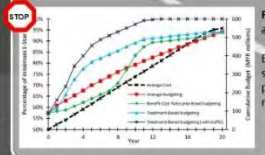


Figure 2 Percentage of 3-star and above network

Effects of all four budget scenario with regards to percentage of 3-star and above network.

6 Acknowledgement

JKR LITROS iRAP

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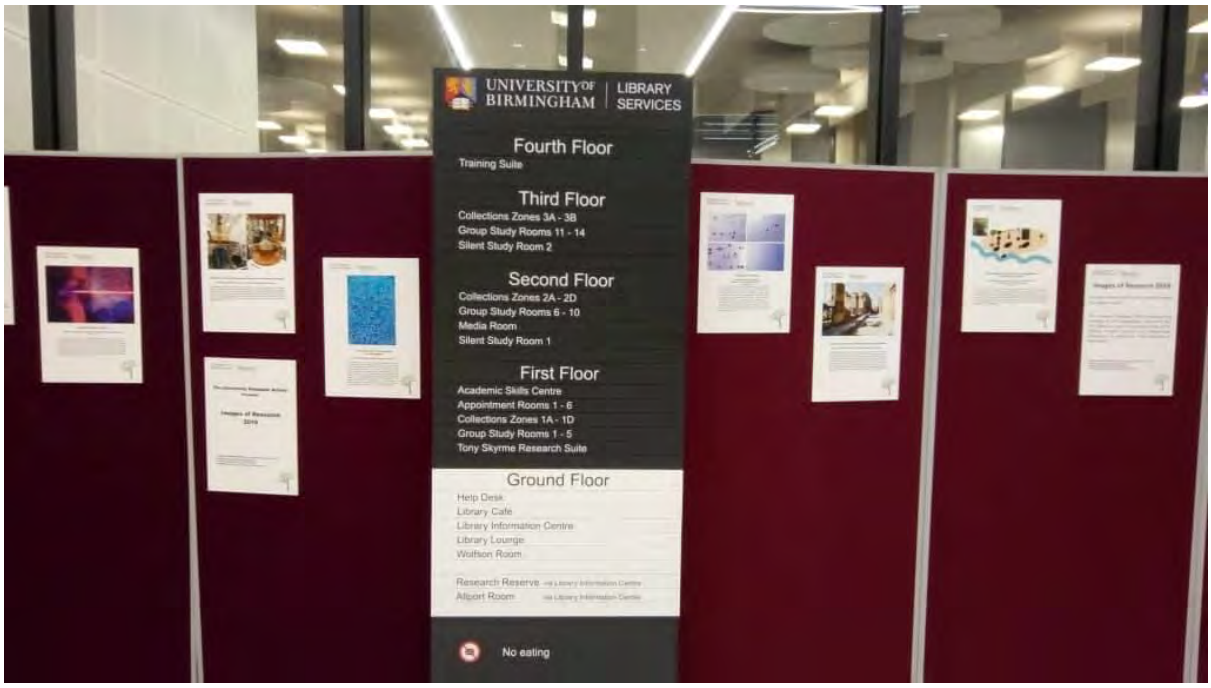
Road Safety or Maintenance: Where Should We Spend Our Money?

***Azwan Azmi*, Civil Engineering, College of Engineering and Physical Sciences**

Road safety and road maintenance are important aspects of road assets management. Implementation of road safety countermeasures will increase the value of the asset. Implementation of road maintenance works will increase the safety rating of the asset. The road safety and maintenance programme need to be integrated in order to optimise the limited road assets management fund. This image depicts the outcome of an integrated road safety and road maintenance programme. It has been taken at an ancient Roman ruin in Italy which has been established around 6th to 7th century B.C. The road safety countermeasures and road maintenance works were implemented in such a high standard by protecting the vulnerable road users and preserving the road assets.



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