ECONOMIC OPTIMISATION OF ROAD NETWORK SAFETY INVESTMENT PROGRAMMES

by

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ABSTRACT

The World Health Organisation (WHO) estimates indicate that 1.35 million people die annually because of road traffic crashes. Socio-economic costs associated with this major global public health concern may be 1-5% of Gross Domestic Product (GDP) in most countries. To reduce this global burden, the United Nations (UN), Bloomberg Initiative for Global Road Safety (BIGRS) and Global Road Safety Facility (GRSF) programmes and initiatives aim at reducing these road traffic crashes. Despite the above concerted effort, road traffic crashes remain a growing public health concern worldwide. The safe system approach endorsed by Organisation for Economic Co-operation and Development (OECD) represents a paradigm shift in road safety management in which support for infrastructure safety investment is one of the priorities. Economic analysis is a critical component of infrastructure safety investment that provides the basis for prioritising and selecting road safety projects or countermeasures. The economic principles and concepts are usually simplified and embedded in road safety investment appraisal models.

To date, no study has conducted a critical exploration, evaluation and synthesis of these models. As a first step, this Thesis systematically reviewed the available models with the aim to integrate and document the current knowledge and its gaps. Cost benefit analysis (CBA) may underestimate economic benefits depending on the approach used, thus the need for sound economic analysis. In practice, crash and casualty-based approaches are used in economic analysis of road safety infrastructure countermeasures most probably without due consideration of the impact of either approach. This research attempts to clarify the economic benefits of these two approaches and their impact in the selection of infrastructure countermeasures through a quantitative study. Financial constraints in road network safety investment programmes and the inefficiency of tools like CBA have led to the growth of economic optimisation tools. Unfortunately, none of the previous developed budget optimisation models considers the life span of countermeasures and their funding. Certainly, without categorising measures, it is possible to preclude the selection of several countermeasures that may enhance a programme's effectiveness within the budget constraints. Therefore, this research develops the concept of countermeasure prioritisation by considering an optimisation method that takes into account both their life span and the available funding to implement an infrastructure improvement programme. To illustrate the application of the proposed model developed using the LINGO software, two case studies from the Netherlands and Indonesia are applied.

According to the results of the systematic review, there are no standardised methods for conducting economic appraisal and the performance of road safety countermeasures. The results of the comparative quantitative study demonstrated that a crash-based approach is more comprehensive and results in a wider range of countermeasures selected for implementation. Furthermore, the results from the newly developed model show that this new approach seems to enhance the prioritisation process. Capital and maintenance countermeasures are equally important. Their importance increases with increasing budget constraints. However, capital and maintenance countermeasures are more important in developing and developed countries respectively. Therefore, this research recommends adoption of a crash-based approach and life span categorisation of countermeasures to improve business cases and effectiveness of road network safety investment programmes.

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LIST OF ABBREVIATIONS

AADT	Average Annual Daily Traffic
AASHTO	American Association of State Highway and Transportation Analyses
ANWB	Algemene Nederlandse Wielrijders Bond (Dutch): The Royal Dutch Touring Club (English)
BCR	Benefit Cost Ratio
BIGRS	Bloomberg Initiative for Global Road Safety
CARE	Community database on Accidents on the Roads in Europe
CBA	Cost Benefit Analysis
CEI	Cost Effectiveness Index
CEA	Cost Effectiveness Analysis
CUA	Cost Utility Analysis
DaCOTA	Data Collection, Transfer and Analysis
DfT	Department for Transport
DOT	Department of Transport
E^3	Economic Efficiency Evaluation
EB	Empirical Bayes
ECMT	European Conference for Ministers of Transport
EPPI	Evidence for Policy and Practice Information and Coordinating
EU	European Union
EuroRAP	European Road Assessment Programme
FHWA	Federal Highway Administration
FI	Fatal and all Injury

FSI	Fatal and Serious Injury
GAMS	General Algebraic Modelling Systems
GDP	Gross Domestic Product
GRSF	Global Road Safety Facility
GSA	Global Sensitivity Analysis
HDM-4	Highway Development and Management
HSM	Highway Safety Manual
iRAP	International Road Assessment Programme
IRTAD	International Road Traffic and Accident Database
ITF	International Transport Forum
LINDO	Linear Interactive Discrete Optimizer
LMICs	Low- and Middle-Income Countries
LSA	Local Sensitivity Analysis
MILP	Mixed Integer Linear Programming
NCAP	New Car Assessment Programme
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development Officers
PDO	Property Damage Only
PIARC	Permanent International Association of Road Congress
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QALYs	Quality Adjusted Life Years
RP	Revealed Preference

RSL	Remaining Service Life
SafetyCube	Safety CaUsation, Benefits and Efficiency
SP	Stated Preference
SPFs	Safety Performance Functions
SRIP	Safer Roads Investment Plan
SWOV	Stichting Wetenschappelijk Onderzoek Verkeersveiligheid (Dutch): Institute for Road Safety Research (English)
TOT	Total crashes
UK	United Kingdom
US	United States
VOC	Vehicle Operating Costs
VOSL	Value of Statistical Life
WHO	World Health Organisation
WTP	Willingness to Pay

LIST OF NOTATIONS

ACC_v	annual construction cost of countermeasure v
CC_V	construction cost of countermeasure v
CC_A	construction cost of shorter service life countermeasure
CC_B	construction cost of longer service life countermeasure
S_V	service life of countermeasure v
R	annual rate of return
CRF	capital recovery factor
S_B	longer service life
S_A	shorter service life
E	effectiveness
CMF	crash modification factor
CMF_C	CMF for the combined countermeasures
CMF_1	CMF for most effective countermeasure
CMF_2	CMF for the second most effective countermeasure
$MCCF$	multiple countermeasure correction factor
$USPWF$	uniform series present worth factor
f_i^c	fatal crash savings for a capital measure i
s_i^c	serious injury crash savings for a capital measure i
sl_i^c	slight injury crash savings for a capital measure i
Pdo_i^c	PDO crash savings for a capital measure i
f_k^m	fatal crash savings for a maintenance measure k
s_k^c	serious injury crash savings for a maintenance measure k
sl_k^m	slight injury crash savings for a maintenance measure k

Pdo_k^m	PDO crash savings for a maintenance measure k
f_c	fatal crash unit cost
s_c	serious injury crash unit cost
sl_c	slight injury crash unit cost
pdo_c	PDO crash unit cost
C_i^c	discounted costs for capital measure i
C_k^m	discounted costs for capital measure k
X_i	binary decision variable for capital measure i
X_k	binary decision variable for maintenance measure k
N	total number of capital measures
K	total number of maintenance measures
B	budget

CHAPTER 1: INTRODUCTION

1.1 Background

Globally, there are 1.35 million fatalities due to road traffic crashes (WHO, 2018). Socio-economic costs resulting from these road traffic crashes may be 1-5% of the Gross Domestic Product (GDP) in most economies (Gorea, 2016; Jadaan *et al.,* 2018; Wismans *et al.*, 2016). Clearly the above figures demonstrate that road traffic crashes have a considerable impact in all countries in this world and to society as a whole.

To reduce this global challenge, the United Nations (UN) General Assembly has adopted a resolution “improving global road safety” with a target of preventing at least 50% of road traffic deaths and injuries by 2030 (UNGA, 2020). This came after realising that the targets in the first decade were not met, thus calling for further concerted effort to reduce crashes. Relatedly, a number of international road safety programmes such as Bloomberg Philanthropies Initiative for Global Road Safety (BIGRS) (Bloomberg Philanthropies, 2022) and Global Road Safety Facility (GRSF) (Dahdah and Bose, 2013) aim at reducing road traffic crashes. Despite the above numerous initiatives, these traffic crashes continue to be a growing public health challenge globally. Novelty thinking during formulation and development of strategies and models respectively is fundamental in boosting investments in road network safety to achieve substantial targets.

Road authorities are primarily responsible for safe design of new roads and safety improvements of existing roads through maintenance and other network strategies. This implies that infrastructure safety investment is a substantial component in new road designs, maintenance and reconstruction works to improve road network safety. A number of countries have adopted the safe system approach endorsed by OECD (PIARC, 2021) that represents a paradigm shift in the planning and management of road safety by prioritising the building of a safe and forgiving road system for all users. A forgiving road system is one that can protect the road users despite their potential errors. The safe system approach is a holistic and systems-based approach that each road authority should follow to maximise the effectiveness of safety countermeasures. When considering road safety interventions including education, engineering, enforcement and emergency services that contribute to crash reductions, road infrastructure appears to be the most significant factor contributing to the crash severity outcome (PIARC, 2021).

1.2 Economic analysis

Economic analysis is a key stage in the planning for road safety infrastructure investments that guides the selection and prioritisation of road safety projects or infrastructure countermeasures. Economic analysis conducted using tools such as cost effectiveness, cost utility and cost benefit analyses determines the use of scarce resources to obtain the greatest possible benefit or the highest return on investments in road safety (Martensen *et al.*, 2018). Road safety investment appraisal models embedding the economic principles of the above tools have been developed to simplify the process. The development of some of these models came from a recommendation by OECD (1997). Unfortunately, no study to date has conducted a critical exploration, evaluation and synthesis of the principles and structure of these investment appraisal models.

The concept of economic analysis for safety infrastructure countermeasures is challenging due to the complex nature of determining the life cycle costs and benefits of countermeasures as well as the crash or casualty unit costs. Consequently, this has led to arguments by Hauer (2011) criticising the cost benefit analysis (CBA) tool that it may underestimate the economic benefits of the countermeasures. There is need for better approaches to economic analysis of road safety infrastructure countermeasures.

1.3 Crash versus casualty economic analysis approaches

In practice, crash and casualty-based approaches are used in economic analysis of road safety infrastructure measures most probably without due consideration of the impact of either approach on the calculated economic benefits and ultimately the selection of countermeasures. The need for substantial economic justification of road safety infrastructure investments is unavoidable with the growing competition for limited funds.

Without improved road safety investment business cases through enhanced computation of costs and benefits of road safety countermeasures, there will always be little progress achieved. Consequently, there is need to identify the most appropriate approach by computing the economic benefits in each approach and further demonstrate their impact in the selection of road safety infrastructure countermeasures.

1.4 Optimisation

Furthermore, economic analysis, as with any other road management decision support tool, may be taken at two levels: project and network. At project level decisions concern detailed investigations of specific road lengths. To date most of the work concerns tools used for project level studies. At network level decisions are associated with strategic management of the entire road network or sub-network. At this level, due to financial constraints, it is necessary to establish and decide on how best to maximise the available budget.

To date, the use of economic analysis tools such as CBA and cost effectiveness may provide important insights to the countermeasures prioritisation process but seem to be inappropriate to handle budget allocation problems (Persaud and Kazakov, 1994). For instance, in a constrained budget, selecting countermeasures based on descending order of benefit cost ratio (BCR) until the budget is exhausted may not yield sustainable and optimal results (Jiang and Sinha, 1990). While previous budget optimisation models (Melachrinoudis and Kozanidis, 2002; Mishra and Khasnabis, 2012; Saha and Ksaibati, 2016) allocated resources amongst measures, highways, intersections or black spots, none of them considers the life span of countermeasures and their funding in the long term or across a road network.

To this end, this research sought to develop an innovative optimisation method that takes into account both their life span and the available funding to implement a road network safety infrastructure improvement programme. Using simplified procedures, the countermeasure selection process may be biased thus affecting the programme's effectiveness most especially under financial constraints. However, an optimisation technique that considers the life span of countermeasures would also improve the sustainability of their assumed economic benefits and guarantee long-term road network safety objectives.

1.5 Problem statement

Road traffic crashes, the casualties involved, and their associated costs are largely preventable provided a comprehensive package of cost-effective countermeasures are included in the planning, design and operation of the road network (Kakkar *et al.,* 2014; Ramadani *et al.,* 2017; Singh *et al.,* 2016).

The economic analysis of infrastructure countermeasures is a key component of a road safety investment programme that determines the economic benefits to inform the prioritisation process (Welle *et al.,* 2018). However, available evidence shows that there is no uniformity in conducting economic analysis of infrastructure safety investments (Byaruhanga and Evdorides, 2021). The economic benefits that enhance business cases presented for road safety investments may be underestimated if for instance instead of analysing crashes, casualties are analysed where a significant proportion of crashes not involving casualties are ignored.

Whereas Elvik (2014) recognised that obtaining the optimal combination in an infrastructure programme is one of the challenges faced by economists and analysts in determining the effective use of countermeasures, all the models (Melachrinoudis and Kozanidis, 2002; Mishra and Khasnabis, 2012; Saha and Ksaibati, 2016) previously developed to prioritise infrastructure countermeasures do not provide a solution to this challenge. Uncertainties regarding the assumed economic benefits resulting from the implementation of infrastructure countermeasures are not addressed by the existing optimisation models. The importance of categorising countermeasures during the prioritisation process has not received due attention. Categorisation may enhance a road network programme's effectiveness and guarantee sustainability of assumed economic benefits.

This research aims at developing a novel approach of prioritising countermeasures by considering an optimisation technique to maximise the computation of economic benefits and enhance the effectiveness of road network safety infrastructure programmes. In particular, the study examines the allocation of the available resources to countermeasures taking into account their life span. In addition to the optimisation technique, this research conducted a quantitative analysis to identify and recommend the most appropriate economic analysis approach and applied existing road network investment programmes as case studies to draw important conclusions.

1.6 Aim and objectives

The research aimed at improving road safety by developing a novel methodology for economic optimisation of road network infrastructure safety investment programmes. The specific objectives were:

1) To conduct a systematic literature review to explore, evaluate and synthesise the structure and principles of the available road safety infrastructure investment appraisal models.
2) To conduct a quantitative comparative study between crash and casualty based economic analysis approaches of road safety infrastructure countermeasures to inform safety analysts and economists on the most appropriate approach.
3) To develop an optimisation model taking into account the life span of road safety infrastructure countermeasures and budget constraints while maximising economic safety benefits to improve the effectiveness of road network safety investment programmes.
4) To demonstrate the practical application of the developed budget optimisation model in prioritising infrastructure countermeasures in road network safety investment programmes.

5) To evaluate the use and relevance of the developed budget optimisation model in developed and developing countries using existing road network investment programmes as case studies.

1.7 Research innovation and novelty

This Thesis seeks to contribute to the body of the existing knowledge and addresses some of the challenges and gaps in the economic appraisal of infrastructure countermeasures. Specifically, the outputs of this research enhance the computation of economic safety benefits and resource allocation problems thereby improving the business cases presented for road network safety investment programmes. The following are the key novelty and additions of this research to the current state of knowledge.

1. A comparative study was conducted as part of this research between crash and casualty economic analysis with the view to clarify which of these two approaches is the most advantageous and appropriate for road safety investments appraisal.
2. The distinction between capital and maintenance investments related countermeasures and a demonstration of the value of this distinction in both developed and developing countries.
3. The use of a formal optimisation procedure for budgeting purposes of road safety infrastructure investment programmes of an entire road network based on a set of objective functions and constraints and automated using linear integer programming.

1.8 Thesis structure

To achieve the aim and objectives of the study, this Thesis adopted the following structure consisting of 11 Chapters, briefly described below.

The first Chapter of this Thesis introduces the study, clearly defining the problem, the aim and objectives, the innovation and novelty in the study including a contribution to the existing knowledge.

Chapter 2 presents the methodological approach. The study conducted a systematic literature review as a first step. In addition, the Chapter presents the methodological framework, quantitative method and a theoretical framework developed to guide the overall structure of the study, knowledge and data requirements.

Chapter 3 presents a systematic literature review of road safety investment appraisal models conducted by the study. Hence, the procedures and standards followed, review questions, search and selection strategies, synthesis of in-depth studies, the analysis and discussion of results are included in this Chapter.

Chapter 4 introduces road safety as defined in transportation engineering. This Chapter highlights the global road safety challenge using economic indicators and annual road traffic crashes. Furthermore, this Chapter presents the road management system and a relatively newer approach to road safety management, the safe system approach that has gained popularity across the globe.

Chapter 5 presents the economics of road safety, which is one of the core elements of a road safety programme that determines the economic value of infrastructure investments.

Chapter 6 presents a comparative study between a crash and casualty economic analysis approaches conducted by this research. In addition, this Chapter presents a comparison between the iRAP approach and the casualty-based approach. The differences, applicability and the impact of these approaches on countermeasure selection are illustrated using case studies.

Chapter 7 introduces the concepts and provides the foundation for the development of the optimisation model through a conceptual model consisting of the objectives, inputs, outputs and constraints. The importance of this Chapter lies in guiding the model development process, validation and forms the basis for model verification.

Chapter 8 presents the development of the optimisation model as a mixed integer linear programming (MILP) problem. Consequently, this Chapter presents the decision variables, objective function and the constraints of the model, which is the final component of model development.

Chapter 9 gives an illustration of the practical application of the developed model using case studies from the Netherlands and Indonesia. The study applied LINGO, a comprehensive and interactive software to run and solve the optimisation problem.

Chapter 10 shows the outputs of the model with the aid of the two case studies including the list of countermeasures prioritised, the budget allocation and economic benefits in each category for the different funding options. This Chapter includes a comparison of the results obtained due to life span and non-life span optimisation approaches.

Chapter 11 presents the conclusions and recommendations for key areas of further work.

CHAPTER 2: METHODOLOGY

2.1 Introduction

A road management system comprises the institutional and management functions, interventions and results (Bliss and Bleen, 2013; PIARC, 2021). Prioritisation, selection and implementation of infrastructure countermeasures is a key element of this system. Determining priority of different measures is an important step during project economic appraisal that requires accurate calculation of costs and benefits of the countermeasures over their life. In most cases however, road safety budgets are limited, implying that not all worthy measures economically justified in a safety programme may be considered.

To address this concern, an optimisation model developed by this research considering the life span of road safety countermeasures and budget constraints seeks to offer practical solutions. A life span categorisation concept is therefore introduced in this Thesis to take into account that costs, and benefits of specific safety measures may differ significantly over their life. Capital measures are not directly comparable to maintenance measures and thus there is a need for a methodology to optimize the budget between these two categories of countermeasures. This Chapter describes the methods employed by this study in order to develop a novel technique that prioritises measures through improved computation of economic benefits.

2.2 Methodological framework

The key research methods and approaches employed to achieve the overall aim in this study include a systematic literature review, a quantitative analysis and a theoretical framework illustrated by the overall approach in Figure 2.1. These are further elaborated below.

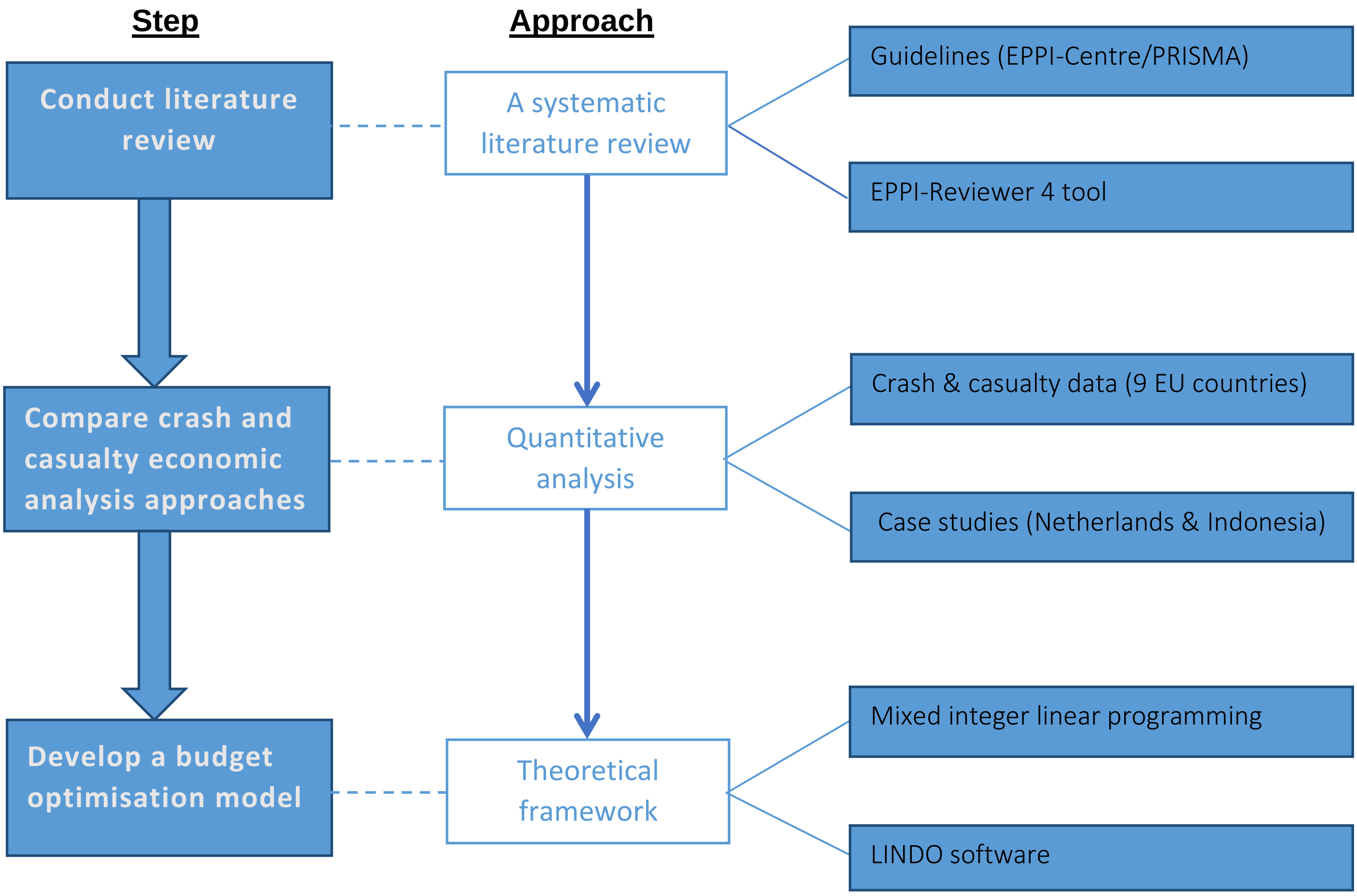


Figure 2.1 Overall approach

2.2.1 Conduct literature review

Fundamentally, literature review forms the basis of any research to understand and analyse the breadth and depth of existing knowledge as well the gaps in a particular area of interest or scholarly topic (Xiao and Watson, 2019). Researchers have used and applied different types of literature review distinguished in terms of speed (time taken), methodological detail, risk of bias and comprehensiveness. Narrative or semi-systematic, critical/integrative and systematic reviews are some of the common applied approaches in conducting literature review (Synder, 2019).

As a first step in any scholarly research, this research conducted a systematic literature review to document the current knowledge and gaps in the computation of life cycle costs and benefits of safety infrastructure countermeasures. A systematic literature review is an examination of the available evidence in a particular area of study based on a clearly formulated question and using a methodical approach to identify, select, critically appraise all the relevant studies and synthesize the findings (Shea *et al*., 2007). Although systematic literature reviews were developed and gained popularity in medical and social science fields, their application in other fields like engineering is also increasing due to their numerous advantages. The main advantage of a systematic literature review is that the review process and research findings are rigorous and transparent (Dixon-Woods *et al.,* 2006). A systematic literature review seeks to minimise bias by using explicit and systematic methods in reviewing the literature thus providing reliable findings that lead to evidence-based conclusions on a particular question(s).

The systematic literature review conducted by this research was guided by the procedures and guidelines developed by the Evidence for Policy and Practice Information and Co-ordinating Centre (EPPI-Centre) for systematic reviews (Gough *et al.,* 2017) and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher *et al*., 2009). EPPI-Centre is a research unit at University College London that provides guidance and training in conducting systematic reviews. This research further utilised the EPPI-Reviewer 4 online tool (Thomas, Brunton and Graziosi, 2010) developed by EPPI-Centre to handle a number of tasks in the review. The research also utilised the PRISMA statement that has improved the quality of reporting for systematic reviews since its inception in 2009 (Panic *et al.,* 2013). The systematic review conducted by this research appears to be the first to examine the available road safety models in order to document the current knowledge and gaps.

2.2.2 Compare crash and casualty economic analysis approaches

Quantitative, qualitative and mixed methods are the three common approaches employed by researchers to collect, analyse and interpret data to understand a phenomenon (Gelo, Braakmann and Benetka, 2008). The decision on which method to adopt depends on the type of data (statistical/numerical, textural or both) needed to answer a research question. Thus, researchers normally choose quantitative approaches or methods while dealing with research questions that involve the use of statistics and mathematical models as a data analysis methodology (Watson, 2015). Quantitative methods that originated from physical sciences quantify information from collected statistical data to draw some conclusions on a research question (Williams, 2007).

This research employed a quantitative approach to compare a crash and casualty economic analysis approaches of infrastructure countermeasures. The main objective of this analysis was to identify and recommend the most appropriate approach to road safety analysts, researchers and economists. Furthermore, although crash and casualty-based approaches are in use to date, apparently, it appears there is no work that has examined the effect of these approaches on the computation of economic benefits and the selection of countermeasures. Consequently, this research clarified and analysed extensively these economic analysis approaches of infrastructure countermeasures using quantitative data. In particular, this Thesis used crash/casualty data from 9 European Union (EU) countries and the road infrastructure programmes developed for the Netherlands and Indonesia as case studies. These two case studies were chosen for comparative reasons but most importantly the need to draw important and firm conclusions based on data from a developed and a developing country. Moreover, the findings of such a comparative study might have a wider application in a number of countries. The Netherlands is one of the developed countries that has experienced an impressive performance in road safety by reducing the total number of traffic accidents by nearly 80% (Elvik, 2010). On the contrary, Indonesia is one of the developing countries with serious road safety challenges. As an example, road traffic crashes are estimated to cause 40,000 fatalities annually in Indonesia (Sutandi and Surbakti, 2012).

2.2.3 Develop a budget optimisation model

In this research, a novel optimisation technique taking into account the life span of countermeasures and budget constraints is suggested to improve the effectiveness of road safety programmes. The development of this model was largely informed by the results of the systematic literature review and the comparative study between crash and casualty economic analysis approaches. Consequently, the model focuses on the differences between crash and casualties and uses linear programming to optimise road safety programmes for subsequent implementation. The key components, approaches used in the development and application of the model are presented in the theoretical framework (Figure 2.2) described below.

2.3 Theoretical framework

2.3.1 A programme of countermeasures

It is fundamental for any country in their management of road safety to have better safety target outcomes, a systematic approach to interventions and an effective institutional management. This research focusses on interventions targeted at improvements to the road infrastructure through engineering principles and design. Safe road infrastructure is one of the five recommended actions of the UN Global Plan for the second Decade of Action for Road Safety 2021-2030 (Job, Truong and Sakashita, 2022). Therefore, a key element in a safety management system is the system wide intervention that focusses among other things on infrastructure countermeasure selection, prioritisation and implementation to prevent, mitigate and reduce traffic accidents and their consequences.

According to Highway Safety Manual (HSM), network screening, diagnosis, selection of countermeasures, economic appraisal, prioritisation of projects and evaluation are the key steps of the roadway management system (AASHTO, 2010). Generally, the major output of this process is the list of recommended countermeasures that are effective in improving the safety condition of the road, termed in this research as the infrastructure countermeasure programme.

This Thesis adopts the iRAP methodology for the roadway management system to develop the countermeasure programme though with some modifications aimed at improving the economic appraisal process. Specifically, a crash based economic analysis approach suggested to be superior to the iRAP's casualty approach for economic appraisal (Byaruhanga and Evdorides, 2022) is preferred in this research. iRAP's countermeasure screening and selection process is adopted because its systemic approach appears to be more effective in improving road safety (Jonathan, Wu and Donnell, 2016) and might produce sustainable results (Byaruhanga and Evdorides, 2021). The other components of the methodology including the computation of countermeasure effectiveness (using crash modification factors (CMF's) or risk attribute factors) and the costs of countermeasures were adopted. Similarly, the minimum economic selection criterion (BCR) ≥1) for countermeasures used in iRAP (iRAP, 2019) and in similar economical appraisal studies (Daniels *et al.,* 2019; Schultz *et al*., 2011) is considered in this research.

Consequently, as presented in the data sources below, this research adopted and modified the 20-year infrastructure improvement programmes for the Netherlands (Utrecht 2014 Provincial Roads) and Indonesia (Bandung 2018 Priority streets) developed using European Road Assessment Programme (EuroRAP) and iRAP respectively (iRAP, 2021). ViDA used to develop these infrastructure programmes is the iRAP's online road safety software that creates and analyses road inspection data to produce safer roads investment plans (SRIP) (Sharma, 2021). The number of casualties (fatalities and serious injuries) computed by iRAP were converted to crash numbers using rations developed from the crash/casualty data for 9 European countries.

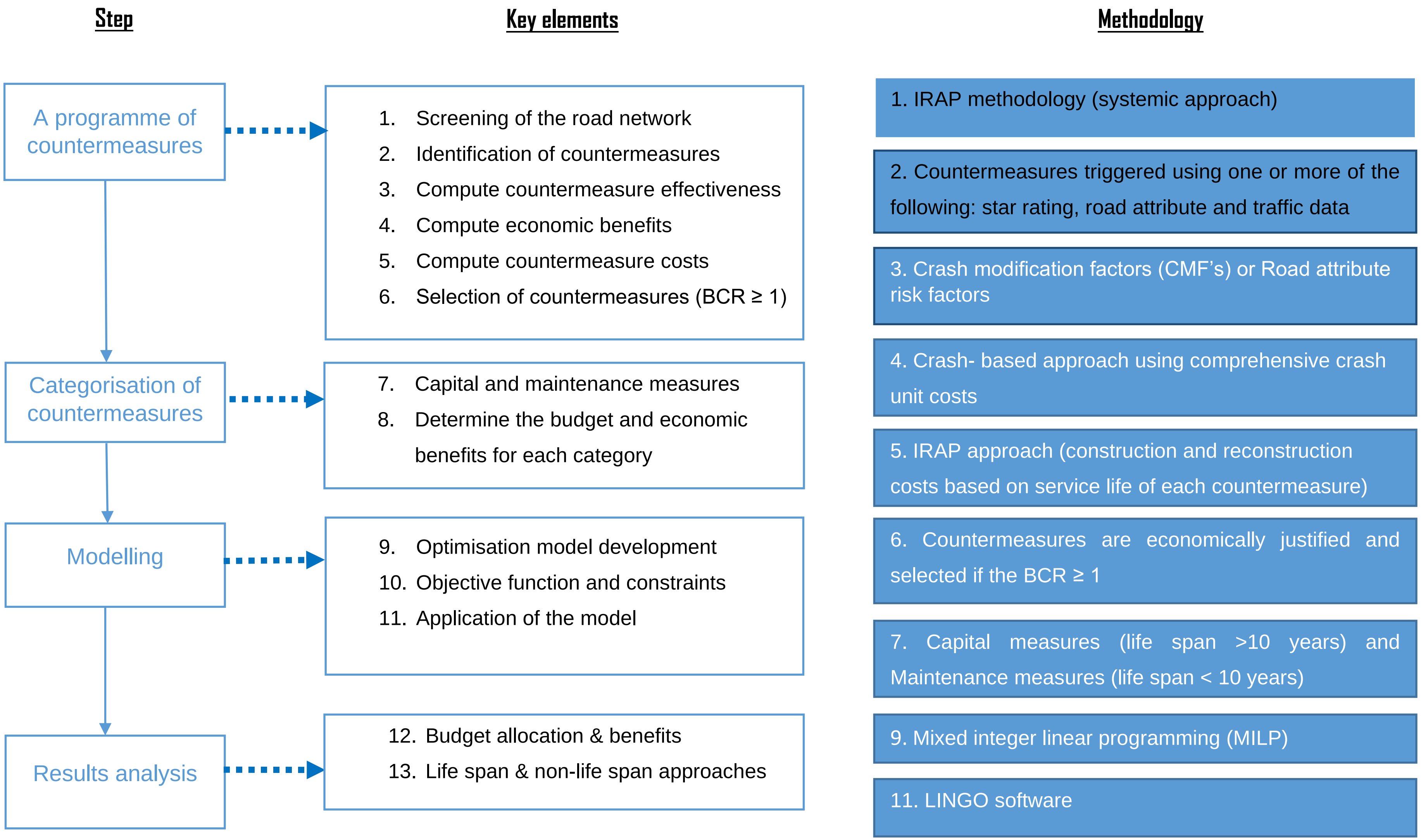


Figure 2.2 Detailed theoretical framework

2.3.2 Categorisation of countermeasures

Road safety infrastructure investments depend heavily on accurate computation of life cycle costs and benefits of road safety countermeasures. Therefore, information about the life span of countermeasures is very important and needed for accurate computation of economic costs and benefits over the analysis or appraisal period. The common terms for the lives of countermeasures include physical, economic and design lives. Physical life is the actual lifetime of the measure beyond which it is useless due to tear, wear or failure (Lemer, 1996). Economic and design lives relate to the performance of the countermeasure with two key dimensions of cost and effectiveness respectively (Lemer, 1996) hence the common use of the term service life. Thus, economic service life is the time of the countermeasure in providing the desired performance while being cost effective (Amer *et al*., 2000). Design service life is the assumed period of time during which a countermeasure or any infrastructure will provide the required performance with the applicable maintenance standard (Chang and Garvin, 2008; FHWA, 2018).

Therefore, it appears that there is a mix of different lives considered during appraisal of safety measures and probably some of these studies use these terms interchangeably. This Thesis adopted the term life span as a common terminology for all the lives applied in the literature. Largely, the study obtained data about the life span of measures from iRAP and other studies. Short-term, medium-term and long-term are some of the terms used to categorise countermeasures based on their life span. The understanding that road safety countermeasures can be implemented as part of a capital or a maintenance works programme (Mahmud, Ahmed and Hoque, 2014; Tziotis, 2011) is tentatively suggested to categorise measures as capital (over 10 years) and maintenance (less than 10 years). With this categorisation approach, this research determined the allocation of resources and the economic benefits for each category of countermeasures in the different budget scenarios.

2.3.3 Modelling

To improve the economic appraisal of the effects of safety infrastructure programmes and to present improved business cases for limited safety budgets, optimisation techniques provide better budget allocations than cost benefit analysis by 35 to 40% (Brown, Bulfin and Deason, 1990). Optimisation techniques have been widely applied in operations research, manufacturing, management, transportation engineering and finance (Mishra, 2013).

Previously, techniques in road safety such as dynamic programming (Brown, 1980), linear programming (Behnood and Pino, 2020; Saha and Ksaibati, 2016; Kar and Datta, 2004) and integer programming (Abdolmanafi and Karamad, 2019; Melachrinoudis and Kozanidis, 2002; Mishra, 2013; Mishra and Khasnabis, 2012) techniques have been applied. The trend shows recent application of linear, integer programming or both and more specifically the use of the faster and more advanced branch–and–bound technique (Przybylski and Gandibleux, 2017). In model development, the modeller requires an objective function to maximise or minimise one or more variables and constraints (Hillier and Lieberman, 2001; Winston, 1997).

Previous models have been used to allocate financial resources to selected measures, black spot areas, specific highways, or locations with no consideration of the life span of countermeasures, their funding and indeed the safety management of an entire road network in a comprehensive and optimised manner. Therefore, this research introduces a novel methodology that prioritises countermeasures of a road network by considering their life span to maximise economic safety benefits.

MILP significantly developed and applied in business and engineering (Vielma, 2015) is utilised in this research to formulate the optimisation problem. MILP is an optimisation modelling technique where the objective function and constraints are linear having both continuous and discrete variables (Maleki, Chabanloo and Taheri, 2019). MILP is chosen due to its ability to include discrete decisions and continuous/discrete variables, thus offering flexibility in solving problems (Richards and How, 2002).

It is felt that effectiveness of a road safety programme highly depends on the best mix between capital and maintenance measures. Thus, one of the constraints of the model ensures a mix between these two categories. The growing competition and limitation of financial resources for road safety infrastructure investments is the other constraint of the developed model.

There are a number of standardised commercial and free academic solver packages available to solve MILP problems. These include Premium Solver Platform (Jiang, 2010), General Algebraic Modelling Systems (GAMS) (Calasan *et al*., 2021) and LINGO (LINDO, 2020). However, this study used LINGO software, which is an efficient comprehensive tool for building and solving optimisation models faster and easier.

2.3.4 Results analysis

Results obtained with the application of the newly developed model are systematically presented showing the unconstrained scenario (100% budget availability) and the constrained scenarios (80%, 60% and 25%). Primarily, tables and figures are used to show the amounts of financial resources allocated to capital and maintenance measures and the resulting economic safety benefits in all the budget scenarios. Tables are also used to show which of the measures are typically selected in each of the budget scenarios. Furthermore, in order to demonstrate the novelty of the approach, the results include a comparison of the life span and non-life span approaches. The above results are presented chronologically for the Netherlands and Indonesia case studies including a comparison between the two case studies.

However, the results and their discussion include a sensitivity analysis. Sensitivity analysis is an important procedure that has gained a widening interest because of its role in model validation and quantitative impact assessment of variables on model outputs (Hendrickson, 1984). Local and global methods are the main methods for sensitivity analysis applicable to linear and non-linear models respectively (Saltelli and Annoni, 2011). Global sensitivity analysis (GSA) mostly applied to non-linear models involves exploring all the space of the uncertain input parameters (Saltelli and Annoni, 2011). Local sensitivity analysis (LSA) estimates parameter sensitivity by evaluating variations in model output with changes in model input variables made one at a time (Likhachev, 2019). This research employed a LSA mostly applied to linear models to conduct parameter sensitivity and model validation. This approach is easy to apply and the results by LSA can easily be explained by the change in input parameters (Likhachev, 2019; Saltelli and Annoni, 2011). The study looks at a possibility of having three or two crash severity levels due to uncertainties and limitations in crash severity data collection most especially for developing countries.

The discussion of all the above results is centred on the interpretation, implication and explanation of the most important findings. Finally, all the above are summarised to draw important conclusions including recommendations for practice and suggestions for future work.

2.4 Sources of data

2.4.1 Community database on Accidents on the Roads in Europe (CARE)

CARE is a European community database created and managed by European Commission that provides high level disaggregated data and information on road traffic accidents/crashes (Olszewski *et al.,* 2016). The quantitative study utilised accident data for 9 European countries (Austria, Finland, Estonia, Germany, Iceland, Ireland, Slovenia, United Kingdom (UK) and Norway) obtained from the CARE database to compare and draw some relationships between crashes and casualties for different severity levels.

The study chose this data due to its appropriateness, high level of disaggregation and accuracy required in the analysis. Specifically, ratios developed and used in this Thesis regarding crashes and casualties originate from this database. The crash/casualty data for these 9 countries obtained from the CARE database is part of the work conducted within the European research project, Safety CaUsation, Benefits and Efficiency (SafetyCube). Generally, data regarding the number of crashes and casualties for different severity levels is limited in the literature but its availability as obtained from the CARE database was a great resource to this study.

2.4.2 Netherlands - Utrecht 2014 Provincial Roads (EuroRAP project)

To compare economic analysis approaches and demonstrate the application of the newly developed optimisation model, the study used SRIP data for a road safety infrastructure programme developed using EuroRAP for Utrecht provincial roads consisting of measures selected for implementation. Utrecht, which is the fourth largest city in the Netherlands, represents a road safety programme developed for a developed economy in which there is evidence for road safety initiatives (Wegman *et al*., 2015; Weijermars and Wegman, 2011). The Netherlands (Figure 2.3), a developed country located in Northwestern Europe bordering with the North Sea, Germany and Belgium is part of the four countries (The Netherlands, Aruba, Curacao and Sint Maarten) that constitute the Kingdom of the Netherlands (Smits, 2012).

It is one of the safest countries in the developed world with the lowest number of fatalities per capita in the world (Wegman, Aarts and Bax, 2008). Its road safety is guided by a safe system approach in which the government continues to support municipal and provincial road authorities in implementing effective road safety countermeasures. For instance, in 2019 there were 3.8 traffic deaths per 100,000 inhabitants recorded in the Netherlands, far below the 5.1 EU average in 2019 (OECD/ITF, 2019). Furthermore, the availability of reliable and accurate data regarding crash/casualty unit costs enabled a meaningful analysis of the different economic analysis approaches applied to road safety infrastructure investments.

Figure 2.3 The Netherlands (Source: Encyclopaedia Britannica, 2022)

2.4.3 Indonesia – Bandung 2018 Priority streets

To demonstrate the wider applicability of the model developed, this Thesis further utilised data from Bandung, which is the second most populated city in Indonesia, chosen as a case study to represent a road safety programme developed for a developing country normally with different traffic flow characteristics that has attempted to reduce the challenge of increasing traffic deaths dominated by motorcycles. The Republic of Indonesia (Figure 2.4), located in Southeast Asia and Oceania, is the world's fourth most populous developing country with the world's most populous Java Island (Hendayana, Supriatna and Imansyah, 2010).

In 2019, there were 11.33 traffic deaths per 100,000 population in Indonesia (WHO, 2022). The recent development in Indonesia to improve the road safety condition was the BIGRS programme phase 1 (2015-2019), in which Bandung was among the 10 chosen cities to implement proven infrastructure countermeasures. Thus, this Thesis used data from the SRIP developed as part of this programme to compare economic analysis approaches as well as in the application of the newly developed optimisation model.

Figure 2.4 Republic of Indonesia (Source: Dreamstime, 2022)

2.4.4 Crash/casualty unit costs

This research used the crash or casualty unit costs as part of the appraisal process to determine the economic benefits of road safety countermeasures in a CBA. These unit costs ensure effective use of the available resources and are key in the economics of road safety investments.

In the Netherlands case study, this research used published standardised average unit costs for the EU, developed and recommended by the SafetyCube project to support member states in conducting economic appraisals (Wijnen *et al.,* 2017). SafetyCube was a research project funded by the European Commission under the Horizons 2020, the EU framework programme for research and innovation that developed an innovative safety decision support system (Thomas *et al.,* 2016). These unit costs are standardised consisting of both injury (medical, production loss, human costs and others) and crash (property damage, administration and other costs).

In the case of Bandung project in Indonesia, crash/casualty unit costs developed by Sugiyanto and Santi (2017) using the human capital method are applied. These unit costs were chosen by this research because they are comprehensive consisting of both direct costs (property damage, administration, medical and loss of productivity) and indirect costs (cost of pain, grief and suffering).

2.5 Summary

This Chapter describes the methodology followed in this research that is made up of a systematic literature review, a quantitative analysis to compare a crash and casualty economic analysis approaches and a theoretical framework based on formal optimisation techniques that guided the model development.

A critical exploration, evaluation and synthesis of the principles and structure of the available road safety investment appraisal models is conducted through a systematic literature review using the EPPI-Centre and PRISMA guidelines.

The increasing global burden of road traffic accidents coupled with the growing competition of financial resources requires substantial economic justification of road safety infrastructure investments. Consequently, this research seeks to develop a novel optimisation technique that takes into account the life span of countermeasures and budget constraints, using appropriate data. The model focuses on the differences between crash and casualties and uses linear programming to optimise road safety programmes for subsequent implementation.

The following Chapters elaborate on this procedure and its innovative components.

CHAPTER 3: SYSTEMATIC LITERATURE REVIEW

3.1 Introduction

As mentioned in the previous Chapter, this research conducted a systematic literature review as a first step to understand and analyse the breadth and depth of existing knowledge as well the gaps in the economic appraisal of road safety infrastructure countermeasures. The economic appraisal of roads is well documented and supported by a number of models such as the Highway Development Management (HDM-4) model (Morosiuk and Kerali, 2001) developed by the World Bank where road safety aspects are to some extent considered. However, a more explicit approach could add significant value.

Therefore, in an attempt to develop a safety-focused model based on the life span of countermeasures, a systematic literature review was conducted by this research to examine the available road safety investment appraisal models with the view to compare and contrast them and ultimately demonstrate the lack of standardisation and uniformity in the approaches used. A review question is the first step in conducting a good systematic review and with the answering of the review question(s), the knowledge and information obtained gives guidance to the planning of a novel research. Consequently, this review formulated and attempted to answer some questions guided by procedures and reporting guidelines for systematic reviews. Therefore, this Chapter presents the review questions, methodology and the results of this systematic review.

3.2 Methodology

There are specific guidelines, procedures and standards developed to guide the process and reporting of systematic literature reviews. The procedures and guidelines developed by Gough *et al.* (2017) at the EPPI-Centre, a research unit at the Institute of Education, University College London, UK and the PRISMA (Moher *at al.,* 2009) were used to answer the following review questions: (i) What road safety investment appraisal models are available and used as decision support systems? (ii) What is the structure and principle of these models? (iii) What are the methods used to define the life cycle of road safety countermeasures? PRISMA is an evidence-based minimum set of reporting items that primarily helps authors to improve the reporting of systematic reviews and meta-analyses. The EPPI - Reviewer 4 tool (Thomas *et al.,* 2010) developed and maintained by the EPPI-Centre performed a number of tasks such as storing retrieved studies, coding, screening and data extraction. The tool used by thousands of reviewers manages and analyses data in literature review and is suitable for small and large-scale reviews for all types of literature reviews.

3.2.1 Search strategy

Literature search databases, engines and organisation websites are all powerful in a comprehensive search to identify all relevant literature in a systematic search. 22 electronic bibliographic databases and 17 organisation websites (Appendix C), search engines such as google, google scholar etc. were searched using search terms (Appendix B) and search operators (phrase searching, truncation, brackets and adjacency or proximity). Boolean operators (AND/OR) were also used to combine the keyword searches. Snow balling technique using the reference lists of relevant studies also led to other studies in this review. Finally, some key road safety professionals also shared some information regarding documentation and appropriate source of data.

3.2.2 Inclusion and exclusion criteria

Published, grey literature and studies in any country relating to the different concepts of the review questions in English language irrespective of the date of study and publication were included. Studies excluded in this review were those in other languages and those not related to road safety investment models or tools, investment appraisal and economic evaluation of road safety measures/countermeasures.

3.2.3 Synthesis

Ultimately, the data extracted from the included studies using the EPPI - Reviewer 4 software was organized and interpreted to answer the review questions, an approach referred to as configurative synthesis (Gough *et al.*, 2017).

3.3 Results

The ultimate aim was to find longitudinal studies indicating the popularity of such models in road management systems used by the road industry. Searching resulted in 903 records (Figure 3.1) being uploaded into the review software. The results of the screening process as per the PRISMA guide (Moher *at al.*, 2009) shown in Figure 3.1 resulted in 12 records meeting the inclusion criteria and thus considered for in-depth review. Of these 12 records, 2 records (AASHTO, 2020; Harwood *et al.,* 2010) documented the SafetyAnalyst model and 4 records (Martensen *et al*., 2016; Martensen *et al*., 2018; Martensen and Lassare, 2017; Van den Berghe *et al*., 2017) described the guidelines and methodological framework for the Economic Efficiency Evaluation (E^3) model. The other 4 records (iRAP, 2013; 2015a; 2015b; McMahon and Dahdah, 2008) described the iRAP model and 2 records (FWHA, 20l9; Lawrence *et al.*, 2018) documented the Benefit Cost Analysis (BCA) model.

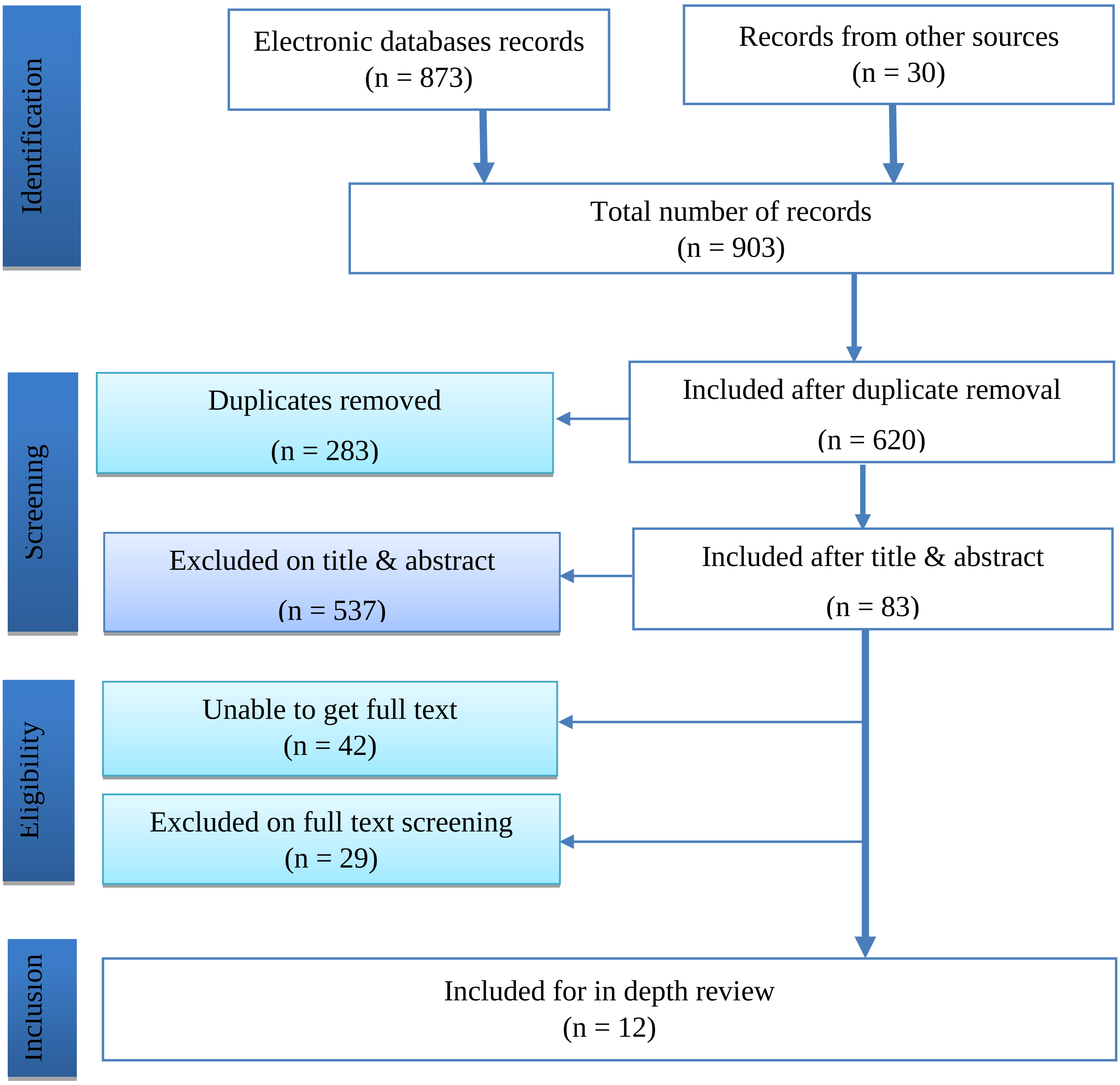


Figure 3.1 PRISMA flow chart for screening of studies

3.3.1 Question 1: Available road safety investment appraisal models

1. **SafetyAnalyst model**

SafetyAnalyst is a set of computerized analytical tools comprising network screening, diagnosis and countermeasure selection, economic appraisal and priority ranking, countermeasure selection and systemic site selection. The tool developed for the Federal Highway Administration (FHWA) aids state and local highway agencies in the United States (US) in safety improvements (Harwood *et al.,* 2010). The software is available for licensing by the American Association of State Highway Transportation officials (AASHTO).

2. **E^3 model**

E^3 is an EU standard model included in the SafetyCube decision support system developed with funding from the European Commission under the Horizon 2020 research framework programme with support from 17 partners from 12 EU countries. The model performs economic evaluation of single measures related to infrastructure, vehicle and human behaviour and not programmes of several countermeasures (Martensen *et al.,* 2018).

3. **BCA model**

BCA is a model developed to support state and local highway agencies in the US to implement procedures described and documented in the Highway Safety Benefit Cost Analysis Guide developed by the FHWA Office of Safety. The model conducts simple economic analysis of infrastructure projects by quantifying costs as well as the direct and indirect safety related benefits of project alternatives (FHWA, 2019).

4. iRAP model

The iRAP model tackles challenging social and economic costs of road crashes. Risk maps, star ratings, SRIP and performance tracking are the four main protocols used in iRAP to assess and improve safety of roads. The iRAP performs economic analysis of single or multiple countermeasures during the preparation of SRIP (iRAP, 2015a). iRAP has conducted programmes in over 100 countries across Europe, Asia Pacific, North, Central and South America and Africa.

3.4 Question 2: Structure and principle of the models

The following criteria (Robinson, 2008) that distinguishes modern road management systems was the basis in examining the constituent components of these models as summarized in Figure 3.2

(1) Road network sectioning

(2) Intervention level

(3) Countermeasure options that may be considered

(4) Complexity of economic analysis and

(5) Countermeasures' prioritisation method.

3.4.1 Road network sectioning

SafetyAnalyst divides the road network into road segments of variable lengths, ramps and intersections unlike iRAP that divides the road network into 100-metre road segments. The other two models (E^3 and BCA) appear not to consider such road management concepts.

3.4.2 Intervention level

SafetyAnalyst uses a crash-based approach whereby the crash frequencies are estimated using safety performance functions (SPFs). SPFs predict crash frequencies for all crash severity levels combined – i.e., fatal and all injury (FI) crashes - as a function of the annual average daily traffic (AADT). In contrast, iRAP uses a systemic approach whereby existing road attributes for every 100-metre segment is the basis for any intervention.

3.4.3 Countermeasure options

SafetyAnalyst provides for selection of a possible array of countermeasures based on the safety problem, crash summary statistics, collision diagrams, statistical crash frequency tests and analyst's knowledge. Similarly, iRAP considers multiple countermeasures for 100-metre segments of road based on a star rating system and road attributes. However, in iRAP, each countermeasure must generate a BCR exceeding a set threshold by the analyst and thus the number of deaths and serious injuries prevented by each countermeasure are required in this process. The E^3 model analyses single road safety measures while the BCA model analyses a maximum of two countermeasures.

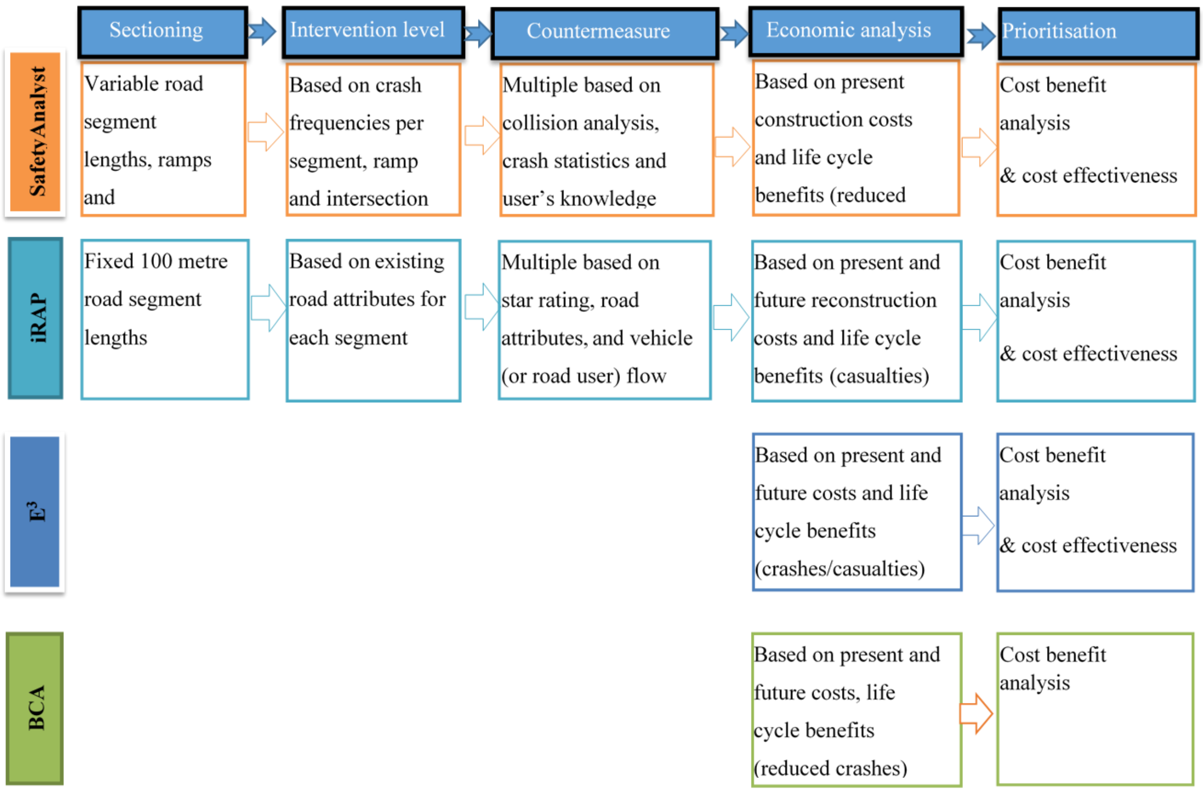


Figure 3.2 Structure of the models

3.4.4 Complexity of economic analysis

Figure 3.2 shows the summary of the basis of the economic analysis conducted by these models. Fatal, serious injury, slight injury and property damage only (PDO) are the severity levels considered in E^3 model. Specifically, fatal, serious injury, slight injury and PDO are the severity levels considering the number of crashes prevented (crash- based approach) while fatal, serious injury and slight injury are considered for the number of casualties saved (casualty-based approach). In this model, the economic appraisal is conducted for the lifetime of the countermeasure determined by the user (between 1 and 50 years). A discount rate defined for each country is applied during economic appraisal in E^3 so as to compare the different streams of costs and benefits.

In SafetyAnalyst and BCA models an additional severity level of possible injury is considered compared to severity levels used in E^3. Economic analysis in these models is conducted for crashes only (crash-based approach). The BCA recommends using a real discount rate (a discount rate that doesn't include the effects of inflation) ranging from 3% to 7% so as to enable meaningful comparison of multiyear dollar costs and benefits. Equally, SafetyAnalyst requires a discount rate to convert the annual costs and benefits to present values.

The economics of the investment plan in iRAP are computed considering a default analysis period of 20 years that maybe adjusted according to the project requirements. A discount rate of 4% is applied to determine the current value of all costs and benefits but maybe adjusted to suit the rate used in each country. The model also computes a default minimum attractive rate of return by dividing the discount rate by 100. The iRAP model is based on a casualty-based approach considering only 2 severity levels (fatal and serious injury).

3.4.5 Countermeasures' prioritisation methods

All the models use cost benefit and cost effectiveness analyses except BCA that uses cost benefit analysis only. In cost benefit analysis, the costs of countermeasures and their monetized safety benefits determine the BCR and the net present value (NPV) of the investment, where a countermeasure is economically justified if its BCR is greater than 1.0 and its NPV is a positive value. Cost effectiveness is generally expressed as the money spent per reduced crash and countermeasures with lower cost per crash reduced are desirable.

3.5 Question 3: Methods for defining the life cycle of road safety countermeasures

Cost and performance of road safety countermeasures during their life span was the focus in answering this review question.

3.5.1 Cost of road safety countermeasures

In SafetyAnalyst (Harwood *et al*., 2010), an annual construction cost $(\mathrm{ACC_v})$ in Equation 3.1 for implementing a single countermeasure is computed using its construction cost $(\mathrm{CC_V})$ and a crash reduction factor (CRF) in Equation 3.2, obtained using service life $(\mathrm{S_V})$ and annual rate of return or discount rate (R).

$$\mathrm{ACC_v} = \mathrm{CC_V} * \mathrm{CRF} \tag{3.1}$$

$$\mathrm{CRF} = \frac{\mathrm{R}(1+\mathrm{R})^{\mathrm{S_V}}}{(1+\mathrm{R})^{\mathrm{S_V}}-1} \tag{3.2}$$

If multiple countermeasures implemented together with the same service lives, the combined cost is the sum of the construction costs of the individual countermeasures. According to AASHTO (2020), if the service lives are different assuming two countermeasures, the combined cost $(\mathrm{CC_{(A+B)}})$ in Equation 3.3 is

$$\mathrm{CC_{(A+B)}} = (\mathrm{CC_A}) + (\mathrm{CC_B})\mathrm{CRF}(\mathrm{R},\mathrm{S_B})\mathrm{USPWF}(\mathrm{R},\mathrm{S_A}) \tag{3.3}$$

$$\mathrm{CRF}(\mathrm{R},\mathrm{S_B}) = \frac{\mathrm{R}(1+\mathrm{R})^{\mathrm{S_B}}}{(1+\mathrm{R})^{\mathrm{S_B}}-1} \tag{3.4}$$

$$\mathrm{USPWF}\ (\mathrm{R},\mathrm{S_A}) = \frac{(1+\mathrm{R})^{\mathrm{S_A}}-1}{\mathrm{R}(1+\mathrm{R})^{\mathrm{S_A}}} \tag{3.5}$$

where CC_A and CC_B are the costs of countermeasures with longer and shorter service lives respectively, S_A and S_B are the longer and shorter service lives respectively and $USPWF$ in Equation 3.5 is the uniform series present worth factor.

In the E^3 model (Martensen *et al.*, 2016), the total cost equals the sum of one-time investment costs and running costs. The BCA model considers total cost as the initial cost (project support, right of way and construction) plus subsequent costs for maintenance, operation, rehabilitation and mitigation. The model provides an adjustment in the case of two countermeasures by standardising the service life using the least common multiple of the service lives, which becomes the analysis period.

In iRAP (iRAP, 2015a), the economic costs are construction and reconstruction costs based on service life data for each countermeasure. This method supports a typical analysis period of 20 years such that a countermeasure with a service life of 20 years gets constructed once, then the one with a service life of 10 years is constructed at the start and reconstructed 10 years later (iRAP, 2015b).

3.5.2 Performance of road safety countermeasures

Performance of the countermeasures over their life span is measured by effectiveness (E) given by Equation 3.6 which relates to the reduced number of crashes measured by a crash modification factor (CMF). A CMF is a multiplication factor, which indicates the number of crashes that would remain after implementing a countermeasure (Martensen and Lassare, 2017).

$$E = 100(1 - CMF) \tag{3.6}$$

In the case of multiple countermeasures, SafetyAnalyst uses a single CMF value to represent the combined effect, which is simply the product of individual CMFs (Harwood *et al.,* 2010). In BCA, when two countermeasures are applied to a crash of the same type and severity, they are analysed to decide whether the two are truly independent, have some overlap or have a counteractive effect. Then the combined factor (CMF_c) is given by Equation 3.7, 3.8 and 3.9 respectively (Lawrence *et al*., 2018) where CMF_1 is the factor for the most effective countermeasure and CMF_2 is for the second most effective countermeasure. In case of complete overlap, the dominant effect method that applies the most effective countermeasure is used.

$$CMF_c = 1 - [(1 - CMF_1) + (1 - CMF_2)] \tag{3.7}$$

$$CMF_c = (CMF_1 * CMF_2)^{CMF_1} \tag{3.8}$$

$$CMF_c = CMF_1 * CMF_2 \tag{3.9}$$

The iRAP model (iRAP, 2013) makes use of a multiple countermeasure correction factor (MCCF) providing a reduction for each individual countermeasure given by Equation 3.10. Further illustration of this adjustment is available in iRAP.

$$\text{Reduction} = \text{Reduction}_{\text{SIMPLE}} * \text{MCCF} \tag{3.10}$$

$$\text{MCCF} = \frac{\text{Reduction}_{\text{MULTIPLIED}}}{\text{Reduction}_{\text{ADDITIVE}}} \tag{3.11}$$

3.6 Economic analysis applicability

To examine the economic analysis applicability of the models, the study analysed cost components, valuation methods and crash or casualty unit costs. The crash unit costs were computed using iRAP methodology and compared to those used in other models. The data regarding crash and casualty unit costs for SafetyAnalyst and BCA was obtained from Harmon *et al*. (2018). This data was appropriate and contained all the severity level unit costs required in the analysis. These recommended unit costs are comprehensive (capturing all the crash impacts) and consist of economic and human costs. However, the unit costs recommended for use in BCA are based on NHTSA's crash and cost estimation report compared to SafetyAnalyst unit costs developed using the Highway Safety Manual (HSM) procedure. Similarly, the unit costs recommended by the SafetyCube project in E^3 obtained from Wijnen *et al.* (2017) are comprehensive and for all severity levels. The above sources of data are reliable and provided relevant, appropriate and quality data used in the review.

3.6.1 Cost components

The review of the 4 models demonstrated that there are differences in the costing methods and components used (Figure 3.3). Accordingly, costs are generally sub-divided into human and economic or injury and crash related costs. In addition, the terms direct and indirect costs are also used. In this review, the terms human and economic costs distinguish between these cost components.

3.6.2 Cost valuation methods

1. Cost of fatalities

In SafetyAnalyst, BCA and E^3 models, the willingness to pay (WTP) approach is the basis in estimating human cost of fatalities. A WTP approach is an attempt to estimate how much money an individual (Individual WTP) or the society as a whole (Social WTP) is willing to pay for a crash risk reduction (Schoeters *et al*., 2017). In determining individual WTP, the revealed preference (RP) and the stated preference (SP) methods are used to trade-off between money and the risk reduction. The RP methods, commonly used in the US, value risk based on actual behaviour while the SP methods; preferred in Europe, use questionnaires to ask respondents how much they are willing to pay for more safety. However, in other studies the gross output, net output, life insurance, court award and implicit public sector valuation approaches have been used (Jacobs, 1995).

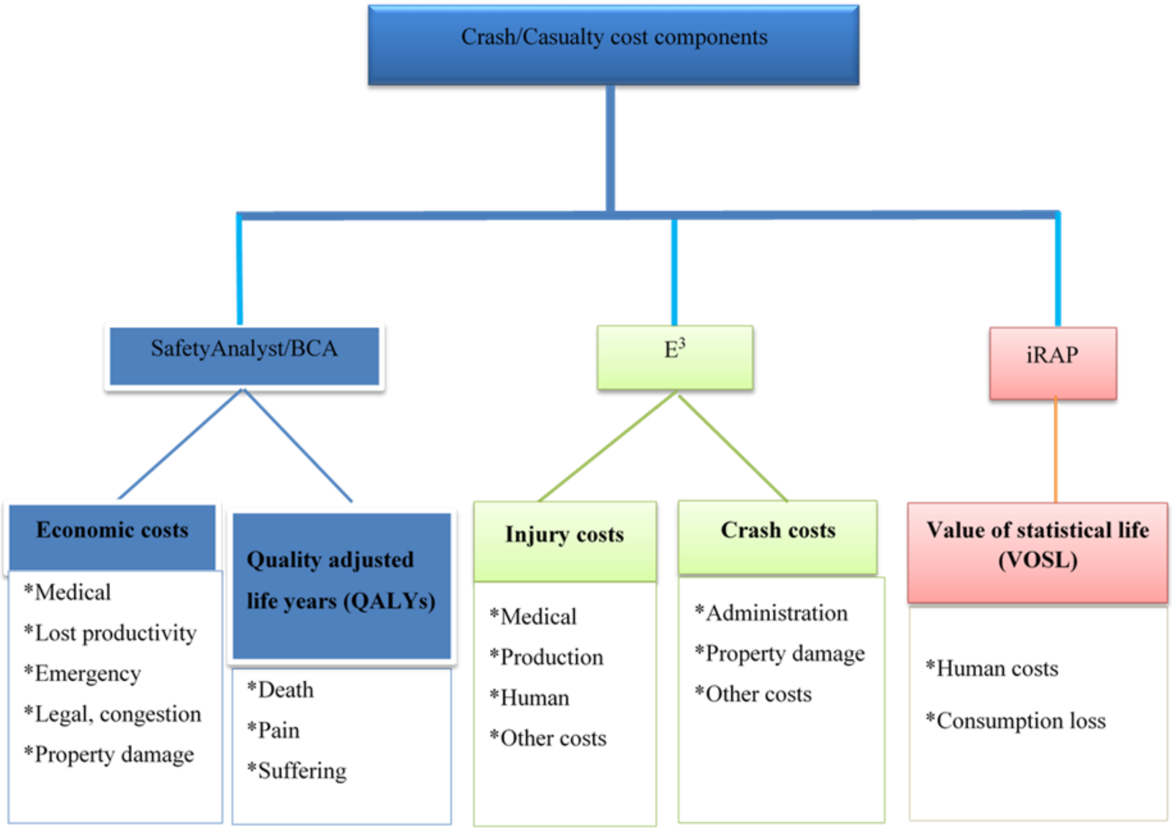


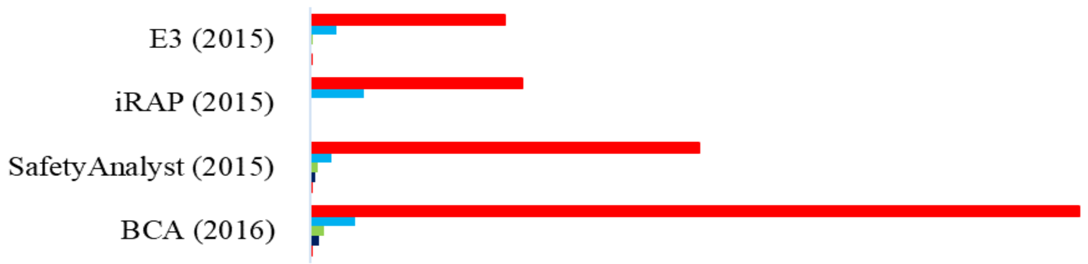
Figure 3.3 Crash/Casualty cost components for the models

2. Cost of non-fatalities

Information regarding the cost of non-fatalities is relatively poor, as many studies have focused on the value of statistical life (VOSL), which leads to the estimation of human costs of fatalities (Schoeters *et al.,* 2017). The cost of a serious injury as a percentage of VOSL is 10-16% by Wijnen *et al.* (2017) and 20-30% by McMahon and Dahdah (2008). Generally, the E^3 model recommends the WTP approach to determine the cost of non-fatalities relative to VOSL. However, in the US where the BCA model is used, quality adjusted life year (QALY) approach values non-fatal injuries determined by the duration and severity of the health problem. The costs for the non-fatal injured victims are in terms of the maximum abbreviated injury scale (MAIS), body part and type of fracture or dislocation (Zaloshnja *et al*., 2004).

3. Crash and casualty costs

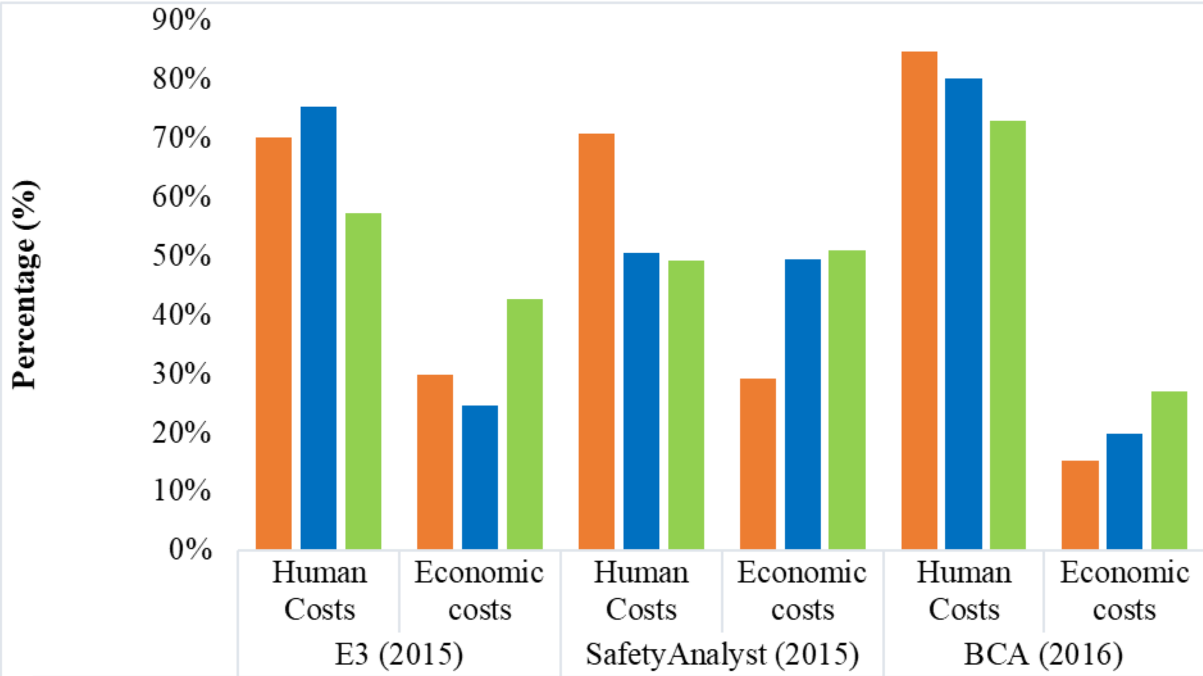
Figure 3.4 presents unit costs for iRAP (computed for UK), SafetyAnalyst (Harmon *et al.*, 2018) and BCA (Harmon *et al.*, 2018) and E^3 (Wijnen *et al.*, 2017) models. In order to compare the differences in the costs considered by each of the 4 models, the iRAP values were computed for UK based on the formula that the value of a fatality is 70 times the GDP per capita and that of a serious injury is equal to 25% of the value of a fatality (McMahon and Dahdah, 2008). The GDP per capita for UK (US$44,495) for 2015 (Statista, 2019) was used.



	BCA (2016)	SafetyAnalyst (2015)	iRAP (2015)	E3 (2015)
Fatal	11,295,400	5,722,300	3,114,650	2,862,789
Severe	655,000	302,900	778,663	389,384
Minor/Slight	198,500	110,700	-	41,447
Possible	125,600	62,400	-	-
PDO	11,900	10,100	-	4,396

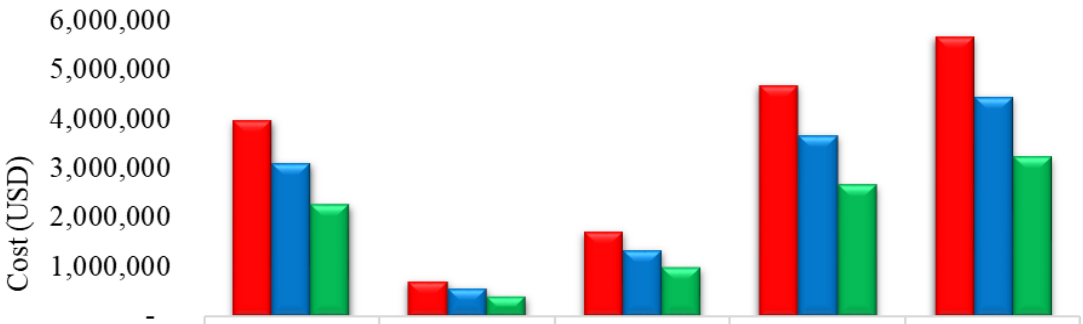
Figure 3.4 Comparison between crash and casualty unit costs used in the models

Furthermore, Figure 3.5 shows the percentages of economic and human costs computed using data by Harmon *et al.* (2018) and Wijnen *et al.* (2017). The comprehensive crash unit cost for a fatality (Figure 3.6) were computed for UK, EU and US based on the iRAP methodology using the 2015 GDP per capita for the US ($56,804), EU ($32,319) and UK ($44,495). Based on the computed VOSL and using the iRAP methodology, the value of a serious injury is US$ 994,061 for US and US$565,590 for EU.



	E3 (2015) Human Costs	E3 (2015) Economic costs	SafetyAnalyst (2015) Human Costs	SafetyAnalyst (2015) Economic costs	BCA (2016) Human Costs	BCA (2016) Economic costs
Fatal	70%	30%	71%	29%	85%	15%
Severe	75%	25%	51%	49%	80%	20%
Minor/Slight	57%	43%	49%	51%	73%	27%

Figure 3.5 Comparison between economic and human costs used in the models



	VOSL	Economic costs: Lower (15%)	Economic costs: Upper (30%)	Comprehensive costs: Lower Limit	Comprehensive costs: Upper Limit
US	3,976,245	701,690	1,704,105	4,677,935	5,680,350
UK	3,114,650	549,644	1,334,850	3,664,294	4,449,500
EU	2,262,362	399,240	969,584	2,661,602	3,231,945

Figure 3.6 Fatal crash unit costs using VOSL and percentages of economic costs

3.7 Discussion

The systematic review aimed at capturing the global practice in the utilisation of road safety economic models as part of road management systems. Subsequently the simple demonstration based on the review showed that the methods used worldwide in determining the cost and performance of road safety countermeasures during their life cycle are not many and not fully consistent and harmonised.

SafetyAnalyst and iRAP are comprehensive decision support tools used for the implementation of safety management plans. Conversely, BCA and E^3 appear to be mere economic analysis models. In addition, the systemic approach (based on existing road attributes) in iRAP appears to be more practical than the SafetyAnalyst’s crash-based and may result in improved network safety in the long-run as compared to the crash-based approach.

E^3 analyses a single countermeasure, the BCA model may consider up to two measures and both SafetyAnalyst and iRAP models can consider multiple countermeasures. This limits the applicability of the first two models because in practice a combination of countermeasures may be implemented at a section, junction and in a road network. However, the iRAP model may also be considered as limited because it takes into account only 2 severity levels (fatal and serious injuries) compared to at least 4 severity levels in BCA, SafetyAnalyst and E^3 models. Furthermore, to determine the combined effect of multiple countermeasures, the multiplicative approach using CMFs is common though it tends to overestimate safety benefits in some studies (PIARC, 2019).

There is no uniformity in all models regarding their economic analyses. The SafetyAnalyst and BCA models utilise crash unit costs whereas iRAP uses casualty unit costs. The E^3 model conducts analysis for either crashes or casualties. Generally, this points out the two different approaches used to conduct economic appraisal of infrastructure countermeasures. The impact on calculation of economic benefits and countermeasure selection process maybe significant and worthy of investigation. The investigation of these economic analysis approaches is important because one of the approaches may underestimate economic benefits thus leading to under investments in road safety.

Crash and casualty unit costs (Figure 3.4) used in all the models are incomparable. Firstly, comprehensive crash costs used in BCA model are on average thrice the E^3 crash unit costs. In the US where BCA model is used, more emphasis is on RP and QALY approaches while the European model E^3 recommends SP and WTP approaches to estimate the costs of fatalities and non-fatal injuries respectively. This may partly explain the difference in crash costs between these two models.

Secondly, iRAP has the highest serious injury unit cost which is twice the serious injury crash unit costs of SafetyAnalyst and E^3 models that are expected to be higher as crashes include one or more vehicles and persons. The methodology used in iRAP to estimate the unit cost of a serious injury appears to be unrealistic and may account for this difference.

The cost of serious injuries as a percentage of VOSL presented as 10-16% by Wijnen *et al.* (2017) is not comparable to 20-30% by McMahon and Dahdah (2008) used in the iRAP methodology. Despite the importance of the above estimation procedure, little research has been conducted to establish a realistic percentage to guide economic appraisal studies of road safety investments in the absence of actual costs.

Furthermore, computed unit costs for serious injuries for EU and US are higher than all the serious injury crash unit costs used in the models, implying that the iRAP methodology may be overestimating the unit cost of a serious injury. The BCA crash costs appear to be unrealistic since fatal crash costs computed for the US and the EU using the iRAP methodology are on average comparable with those used by SafetyAnalyst and E^3 models unlike those by the BCA model. The different data sources may possibly account for these incomparable unit costs between SafetyAnalyst and BCA.

All the models consider the human and economic costs in their cost components except iRAP that considers only human costs. Further analysis shows that human costs have a major share over the total crash cost and on average up to 70% compared to 30% of other economic costs. Interestingly, the BCA model which has the highest crash unit costs has the least (15%) and highest (85%) percentage of economic and human costs respectively. This may further be used to explain the high unit costs in BCA model where human costs constitute an average of 80% of the crash unit costs.

The computation of countermeasure costs during appraisal differs in all methods and the end-of-life costs are not considered. Ideally, a life cycle approach should consider all the costs incurred during planning, design, building/construction, operation, maintenance and disposal in road project appraisal. SafetyAnalyst's cost computation approach offers the strength of an annualised cost method, which may be applicable to multiple treatments with unequal service lives.

The results of this review clearly indicate that most of the models do not consider indirect benefits (reduced travel delays, VOC and emissions) except the BCA tool making it unique compared to other models. This is contrary to the recommendations by EC (2018), Martensen and Lassarre (2017), OECD/ITF (2015) and SWOV (2011) to include indirect benefits in CBA of safety countermeasures. Again, little is known about the impact of indirect benefits on the computation of economic benefits and countermeasure selection process. The quantitative impact of indirect benefits in the economic appraisal process is important in improving the consistency and reliability of investments in road safety.

Finally, in all the appraisal models reviewed, prioritisation of infrastructure countermeasures is conducted using CBA and CEA tools. However, the use of these tools alone considering financial constraints of road safety infrastructure investments is ineffective (Persaud and Kazakov, 1994). Consequently, this has led to the development and use of optimisation techniques in the prioritisation process. Unfortunately, the optimisation models developed up to date (Melachrinoudis and Kozanidis, 2002; Mishra and Khasnabis, 2012; Saha and Ksaibati, 2016) still do not offer an optimal combination of countermeasures. These existing optimisation models mainly focus on allocating available funds to black spots, sections of the road network etc. and do not consider categorisation of countermeasures and their source of funding. Categorisation is an important aspect in prioritisation because sustained performance highly depends on the life span of countermeasures and their funding requirements. Elvik (2014) and Sabey (1980) earlier pointed out the need for strategies and techniques required to obtain optimal combination or balance between countermeasures. The development of a technique/methodology to achieve the above is important to improve the effectiveness of road safety investment programmes. Unfortunately, very little research has been conducted to adequately provide a solution to this challenge.

3.8 Summary

In an attempt to develop a safety-focused model based on the life span of countermeasures, this review examined the available models with the view to document the current knowledge and its gaps. The systematic literature review followed the procedures and guidelines developed at EPPI-Centre and PRISMA reporting guidelines.

Searching and screening process resulted in 12 studies that documented and described the guidelines and methodological framework for SafetyAnalyst, E^3, BCA and iRAP models that are widely used.

The results of the systematic review show that the methods and approaches applied worldwide in determining the cost and performance of road safety countermeasures during their life cycle are not many and not fully consistent and harmonised. SafetyAnalyst and iRAP are comprehensive decision support tools unlike BCA and E^3 that appear to be economic analysis models. There are no standardised methods for combining life cycle costs of road safety countermeasures during appraisal and all approaches ignore end of infrastructure life costs. There is neither uniformity nor universally accepted standards to estimate crash or casualty unit costs and the life cycle performance of road safety countermeasures.

The next Chapter defines road safety and presents some of the approaches in road safety management.

CHAPTER 4: ROAD SAFETY

4.1 Introduction

Safety in transport relates to the freedom from unacceptable risk of death or physical injury and of damage to property and to the environment (Formela, Weintrit and Neumann, 2019). Road or traffic safety is thus the study of the state of the road in which hazards and conditions leading to traffic and road risk are controlled, managed and reduced (SafetyNet, 2009). Road safety is important to the wellbeing of people and to the country's economic growth as roads are essential for the movement of people and goods.

However, it is unfortunate that traffic accidents result into considerable numbers of fatalities and casualties in most countries; meaning that the transport-planning objective to achieve safety is challenging. This is a global issue because everyone needs to be safe and more importantly that every country must ensure a decrease in these crashes for the safety of its residents, travellers on either business or leisure trips.

Consequently, there has been tremendous effort by large body organisations, governments, civil society, funders and the private sector to tackle the global road safety crisis. Most recently in September 2020, the United Nations (UN) adopted a resolution to improve global road safety proclaiming the Decade of Action for Road Safety 2021-2030 with the ambitious target of preventing at least 50% of the road traffic fatalities and injuries by 2030 (Job, Truong and Sakashita, 2022). This may be difficult to achieve based on the previous performance of the Decade of Action for Road Safety 2011-2020 (WHO, 2011). However, it provides opportunities for harnessing the successes and lessons of previous years to build further on them to save more lives.

4.2 Global road safety

According to WHO (2018), road traffic crashes are responsible for 1.35 million fatalities and 50 million injuries annually and are the leading killer of children and young people aged 5-29 years world-wide. Estimates further show that vulnerable road users (pedestrians and all cyclists) are about 50% of these traffic fatalities. Although it is a global pandemic, 90% of these road traffic crashes occur in low and middle-income countries (LMICs) (WHO, 2018). For instance, the average fatality rates in Africa and Southeast Asia are 26.6 and 20.7 deaths per 100,000 inhabitants respectively, while in America and Europe, it is 15.6 and 9.3 deaths per 100,000 inhabitants respectively (WHO, 2018). In 2019, the 14th report on road safety performance (Carson, Adminainte-Fodor and Jost, 2020) shows that 22,660 traffic deaths occurred on EU roads translating to over 400 fatalities a week.

In addition to the grief and suffering of individuals, families, societies and nations, there are significant economic losses due to these crashes. The economic consequences of traffic crashes are generally high. They vary across different countries, costing 1-5% of the GDP (Jadaan *et al*., 2018; Gorea, 2016; Wismans *et al.,* 2016).

There is great success in reducing this global crisis in many high-income countries despite the increasing population and rapid motorization (Ameratunga, Hijar and Norton, 2006). Nonetheless, these preventable numbers of fatalities and casualties and their impacts are still unacceptable from a global health and development point of view (World Bank, 2017). Therefore, to make a significant improvement in this crisis, concerted effort is still required in research, policy and practice worldwide.

The causes of road traffic crashes are complex involving the interaction of vehicle, human and road infrastructure related factors (Touahmia, 2018). Nonetheless, there has been some progress to identify some approaches and initiatives to improve the road safety situation.

4.3 Road safety management

Road safety management is the systematic process aimed at preventing or reducing the number and severity of road traffic crashes (Muhlrad, Gitelman and Buttler, 2011; Varhelyi, 2016). Furthermore, Papadimitriou and Yannis (2013) describe road safety management based on three key aspects: “vision and strategy”, “budget, evaluation and reporting” and “measurement of road user attitudes and behaviours”. In the Road Safety Data, Collection, Transfer and Analysis (DaCOTA) project, institutional organisation, coordination and stakeholder involvement, policy formulation and funding, monitoring and evaluation, scientific support and information, capacity building were considered to be the main five areas of road safety management (Papadimitriou *et al*., 2012).

Road safety management plays a fundamental role in reducing the high cost of motorized mobility to individuals, families and society. In the exhaustive investigation of road safety management in European countries by Papadimitriou *et al*. (2012), despite a number of good practice elements, it was not possible to identify one single good practice model at the national level regarding structures, processes and outputs of road safety management. In the same study, there was no direct link between road safety management and the outcomes regarding fatalities and injuries. Equally it has been argued that effective road safety management is complex and requires various structural and procedural forms making it difficult to identify a single good practice model or describe it in a standardised way (Bliss and Breen, 2013; Papadimitriou and Yannis, 2013). Although countries with the best safety performance record have common characteristics regarding their target safety outcomes, approach to intervention and institutional arrangements (PIARC, 2021), this may not truly reflect the existence of best practice in road safety management (Johnston, 2010; Papadimitriou *et al*., 2012).

Generally, road safety production process viewed as a management system with three distinctive elements (Figure 4.1) may lead to improved road safety performance (Bliss and Green, 2013; PIARC, 2021). Although discussions by researchers, organisations and countries concerning road safety improvements focus on interventions, assessing all the three elements and their linkages is critical for any country seeking to improve road safety. Road safety performance depends on institutional capacity to implement efficient interventions shaped to achieve the desired focus on results. Whilst this is possible and as seen from above, road safety management is a complex subject since a harmonized structure or system that relates with the best road safety performance does not exist (Papadimitriou and Yannis, 2013).

Consequently, the global challenge of road traffic crashes and the associated socio-economic costs have progressively pushed most countries into a results-oriented approach culminating into the safe system approach to road safety management. The latest Global Plan for the Decade of Action for Road Safety 2021-2030 developed by WHO and UN Regional Commissions is calling governments and partners to take a new path that prioritises and implements an integrated safe system approach.

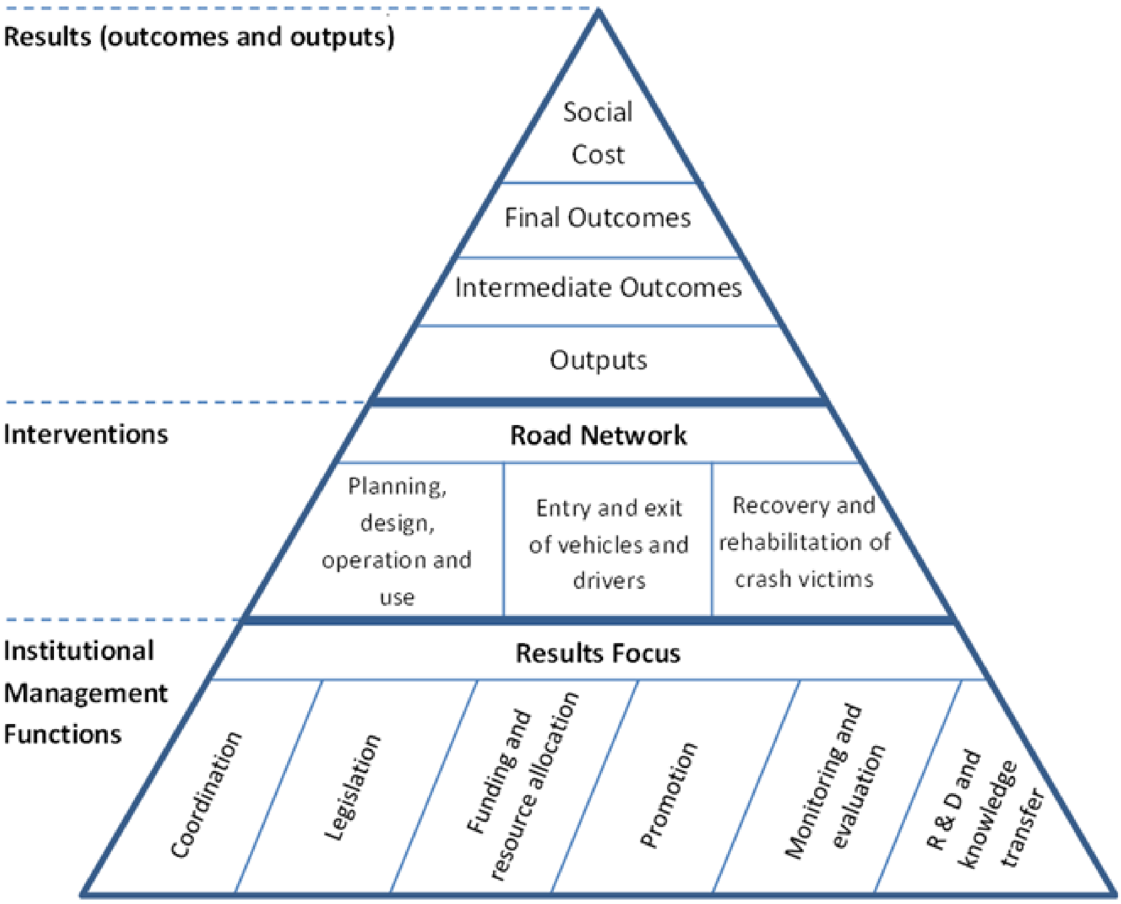


Figure 4.1 Road safety management system (Source: Bliss and Green, 2013)

4.4 Safe system approach

This is a Swedish concept that shares similar principles and concepts to the Dutch sustainable safety philosophies (PIARC, 2021; Mooren, Grzebieta and Job, 2013; Larsson and Tingvall, 2013; Welle *et al.,* 2018) encompassing a systems approach to road safety, recognising the need for collaboration and shared responsibility between users, designers and operators to minimise crash outcomes. This approach seeks to ensure that road users are not subject to kinetic energy exchange in the event of a crash that will result in death or serious injury (PIARC, 2021; OECD/ITF, 2008).

Generally, the safe system approach has gained popularity across the globe following its successful implementation over regions and in many countries. There is evidence of improved safety after implementation of the safe system approach and the world's most successful safety performance relates to policies and plans guided by this approach. The Netherlands and Sweden are among the countries with the most impressive progress in improving road safety due to the implementation of this approach. Similarly, the number of road fatalities declined by 42% between 2000 and 2013 in 32 member countries of the International Road Traffic and Accident Database (IRTAD) due to the implementation of systematic road safety strategies and programmes (OECD/ITF, 2015).

Consequently, the OECD recommends all countries to adopt a safe system approach irrespective of their level of safety performance (OECD/ITF, 2008). In addition, the guiding principles underlying the Global Plan for the Decade of Action 2021-2030 reject the business as usual and call governments and stakeholders to embrace and implement an integrated safe system approach.

4.4.1 Principles of a safe system approach

According to ITF (2016), the key principles of the safe system approach are as follows:

i. Human beings by nature make mistakes or errors while using the road system, so crashes/accidents will always occur. The interaction between the road user and the physical, social and technical environment is complex leading to numerous errors and misjudgements and so those designing the road and vehicles need to understand such complex interactions to accommodate human mistakes.

ii. Human body is limited physically and so vulnerable to death and injury in the event of a road crash/accident. The level of kinetic energy that a human body can withstand before a crash results into death or injury is very low, thus the need for a system that is human-centric and accommodates human vulnerabilities.

iii. A shared responsibility to those who design, build, manage and use the roads and vehicles to prevent crashes resulting in fatalities and serious injury. Policy makers, Engineers/Designers, Planners, Enforcement officers, Health agencies, media and other stakeholders should be involved equally in eradicating fatalities and serious injuries.

iv. The need for an integrated approach in road safety to multiply their effects protecting road users in case one part fails. A safe system approach calls for strengthening all parts of the road system to achieve a solid combination of systems covering each other in case of an error.

4.4.2 Elements of a safe system approach

According to Safarpour, Khorasani-Zavareh and Mohammadi (2020), the key pillars or elements of the safe system approach are;

1. Infrastructure (safe roads and roadsides),
2. Improved vehicle design (safe vehicles),
3. Safe road use (safer road users),
4. Reduced speeds (safe speeds) and
5. Effective post-crash response and medical care (post-crash care).

These are further elaborated below.

1) Safe roads and roadsides

A safe infrastructure is essential in reducing traffic crashes and is the single most significant factor that influences the severity outcome of a crash (PIARC, 2021). Infrastructure design, construction and operation should eliminate all risks for all road users with much emphasis on vulnerable road users supporting multimodal mobility, including public transport, walking and cycling. Therefore, continuous review of infrastructure design standards to reflect safe system approach principles is an important step to provide safe roads. These technical standards must ensure and cover the safety needs of pedestrians, cyclists, motorcyclists, vehicle occupants, public transport users, freight operators and other mobility users.

In addition, there is always a need to assess the built road infrastructure so as to ensure it is safe for all users. Consequently, as identified in Chapter 3, iRAP is one of the tools developed and used widely for road network screening process. This tool as previously discussed employs the systemic approach where countermeasures are implemented based on high-risk roadway features and deficient sections of the road network. Examples of countermeasures used in this Thesis that were developed using the iRAP tool are presented in Table 6-6 and Table 6-7.

2) Safe speeds

Excessive and inappropriate speed is a widespread social problem that contributes to one third of fatal accidents in most countries (OECD/ECMT, 2006). At the start of the COVID-19 pandemic in 2020, countries that registered increasing number of crashes were due to increased speeds resulting from reduced movement of people and goods (Yasin, Grivna and Abu-Zidan, 2021). There is evidence that with the best road and vehicle design features, there is no guarantee for safety movement of all users with speeds above 30km/h (Neki *et al.*, 2021; Tingvall and Haworth, 1999). In ensuring safe speeds, safe system approach aims at enforcing and educating the road users about the existing speed limits as well as setting appropriate speed limits according to the features and standard of the road. Speed limit enforcement provides immediate safety benefits than any other single measure. Generally, managing speed is a critical element to effective implementation of a safe system approach and central to building a forgiving road transport system.

3) Safer road users

This element concerns the development of road users with sufficient information, knowledge and skills to make rational and correct decisions and to follow rules and procedures for correct behaviour. For instance, the approach addresses the safety needs for all users, inspires people for active modes of transport such as walking, cycling, and encourages public transport use as opposed to private car. In addition, the approach puts emphasis on helping and supporting all road users to comply with the rules such as use of safety belts, helmets and child restraints, drunk and distracted driving. The safe system approach presents a new way of looking and understanding road user behaviour and errors by acknowledging human fallibility and frailty.

4) Safe vehicles

Vehicle safety regulated through design standards and safety features such as autonomous emergency braking, seat belts and airbags and maintained through mandatory vehicle inspection schemes or roadworthiness tests is one of the most important elements of a safe system approach. Consequently, the adoption of the UN most important motor vehicle and crash test standards at the point of manufacture, supported and promoted by the Global New Car Assessment Programme (Global NCAP) aims to improve the safety of vehicles (Ward, 2014). Vehicle designs and standards that reduce human error and impact of collision are an important action in reducing fatalities and serious injuries. Road safety agencies and road authorities should promote and monitor the benefits of safety features such as inbuilt alcohol and fatigue detectors, intelligent speed adaptation, collision avoidance and overall vehicle safety standards.

5) Post-crash care

The outcomes of crash victims rely on a post-crash response system to quickly locate and provide the necessary emergency care to stabilise the victims and for further care and treatment in a hospital. Post-crash response is very important because a delay of a minute is substantial in determining the survival chance and quality of life. A comprehensive package starting with research and information, alert system, trained personnel and necessary equipment, rehabilitation, trained community first responders and the requisite legal support and legislation are key components of a post-crash response. Ultimately, post-crash care aims at preventing death and limiting the severity of the injury as well as ensuring optimal functioning of the crash victims and reintegration into the community.

4.5 Summary

Road safety is the study of the state of the road in which hazards and conditions leading to road risk are controlled, managed and reduced. Road traffic crashes are responsible for over 1.3 million fatalities and 50 million injuries annually and are the leading killer of children and young people aged 5-29 years worldwide. Although it is a global pandemic, 90% of these road traffic crashes occur in LMICs. Traffic crashes are estimated to cost most economies 1-5% of their GDP in socio-economic terms.

Due to this challenge, there has been tremendous effort by large body organisations, governments, civil society, funders and private sector to tackle the global road safety crisis. Globally and most recently, the UN adopted a resolution to improve global road safety proclaiming the Decade of Action for Road Safety 2021-2030 with an ambitious task of preventing at least 50% of the road traffic fatalities and injuries. Arguably, effective road safety management is complex and requires various structural and procedural forms making it difficult to identify a single good practice model or describe it in a standardised way. A relatively newer approach is the safe system that shares similar principles and concepts to the Dutch sustainable safety philosophies.

The next Chapter introduces the economics of road safety, a key element of a road safety infrastructure programme.

CHAPTER 5: ECONOMICS OF ROAD SAFETY

5.1 Introduction

Economic analysis of road safety interventions is one of the core elements of a road safety programme aimed at determining accurately its economic benefits (Welle *et al.*, 2018). This analysis allows organisations to identify, quantify and determine the value of economic costs and benefits of chosen interventions over the appraisal period to ensure efficiency and effectiveness of safety programmes (U.S. DOT, 2003).

There is a cost and benefit associated with every road safety intervention. Every country has a limited road safety budget and financial constraints are difficult to overcome, so selection of the most cost-effective safety policies delivering optimal safety outcomes for the lowest cost are necessary (PIARC, 2021; Yannis *et al*., 2016). This process requires good knowledge about the effectiveness of road safety interventions that can be best achieved through economic appraisals or evaluations. The criteria applied in deciding about road safety policies include suitability, lawfulness, and/or legitimacy together with economic efficiency (Yannis *et al.,* 2016).

Therefore, economic appraisal is an important tool in the hands of decision makers that enables efficient use of limited resources and may guarantee significant changes in road safety performance. The economics of road safety interventions helps in understanding the economic efficiency of additional spending on policies targeted at road safety improvement.

Generally, the purpose of economic appraisals in road safety interventions is to rank or prioritise activities by their economic returns and to justify public money expenditure. However, economic analysis for safety interventions is quite challenging due to the complex nature of determining the life cycle costs and benefits of countermeasures as well as the crash or casualty unit costs. In addition, there are still arguments regarding the best approach to estimate crash unit costs and benefits from multiple countermeasures implemented together. Consequently, there is no uniformity and universally accepted methods for computing unit costs and the life cycle performance of infrastructure measures (Byaruhanga and Evdorides, 2021).

The economic analysis of road safety policies is determined using economic tools, which enable rational decision making and identification of the most cost effective and beneficial road safety interventions. To this end, this Chapter presents some of the tools, techniques and economic analysis approaches widely used today for infrastructure measures.

5.2 Key components

5.2.1 Costs of infrastructure countermeasures

The cost of countermeasures is one of the key components in conducting economic appraisal of road safety infrastructure countermeasures. In Yannis *et al.* (2008), the implementation costs of safety measures are the investment costs and the annual costs of maintenance and operation. Costs considered in life cycle cost analysis (LCCA) are those incurred by the highway agency and the road user (Heidari, Heravi and Esmaeeli*,* 2020; Moins *et al.,* 2020; Gobis, Jamroz and Jelinski*,* 2020; FHWA, 2002). However, Chan (2007) adds the external indirect costs incurred by the nonpublic user such as pollution costs. Emission of greenhouse and toxic gases, water pollution and noise are considered under environmental costs (Qiao *et al.,* 2019).

Generally, economic, social and environmental costs are the three main components in life cycle costing (Karim, 2011; Wennstrom, 2014; Hoogmartens *et al*., 2014). Road authority costs are associated with planning, design, construction, maintenance, operation and disposal of an asset or measure. Social costs relate to the road user such as vehicle operating costs (VOC), travel time costs etc. and the impacts related to health and wellbeing (Hoogmartens *et al.,* 2014) while environmental costs consider the impacts on the environment during production, usage and disposal.

There are limited methods and difficulties to compute the monetary value of environmental impacts (Qiao *et al.,* 2019) and equally incorporating road user costs in life cycle costs is full of uncertainties (Giustozzi, Crispino and Flintsch*,* 2012; Salameh and Tsai, 2020). The following economic life cycle costs incurred directly by road agencies from planning to disposal recommended by Lawrence *et al.* (2018) may constitute infrastructure countermeasure costs.

I. Initial capital costs during planning, right of way acquisition, design, construction/installation (including overhead and administration costs) and other costs related to environmental protection and traffic maintenance during implementation.
II. Operation and maintenance costs such as power costs of signals, periodic pavement marking, communications, repairs and replacement, labour and routine maintenance.

III. End of project costs such as salvage or residual values.

The end of project costs are in most cases excluded in computing life cycle costs despite having substantial impact (Moins *et al.,* 2020).

5.2.2 Benefits of infrastructure countermeasures

In CBA of road safety countermeasures, it is important that all relevant effects on safety, travel time, environment and operational conditions are taken into consideration as these have a substantial influence on the results of a CBA (Martensen and Lassarre, 2017). Generally, the benefits are categorised as direct and indirect benefits. In most studies for countermeasures, the direct safety benefits of countermeasure implementation considered are the reduced number of crashes or injuries (Daniels *et al*., 2019; Lawrence *et al.,* 2018). Similarly, most of the widely used road safety investment appraisal tools such as SafetyAnalyst (AASHTO, 2020) and iRAP (iRAP, 2015) consider safety benefits relating to reduced number of crashes or casualties. In recent years, there has been research effort to standardise methods for estimating these direct safety benefits of countermeasures (Hasson *et al*., 2012; Yannis, Weijermars and Kauppila, 2012).

The term indirect benefits refers to those positive impacts of road safety countermeasure implementation that result from a change in safety performance (reduced number of crashes) such as reduced travel time, improved travel time reliability, reduced fuel use and reduced emissions (FHWA, 2018). The E^3 tool allows analysts to include indirect benefits of safety measures although their actual computation was not included in the scope for the SafetyCube project (Martensen *et al*., 2018). Unfortunately, most economic appraisal studies appear to ignore the indirect benefits due to lack of models to evaluate them (Yannis *et al.,* 2008). In fact, indirect benefits may be positive or negative and are often looked at from two angles: firstly, due to implementation of a safety measure and then as a residual benefit due to the reduction of crashes.

5.3 Economic efficiency

Economic efficiency is the process of determining the profitability of an investment by comparing the costs and the results (Mykhailenko, 2018). Cost effectiveness, cost utility and cost benefit analysis are the tools used to determine the economic efficiency (Drummond *et al.,* 2015). However, cost effectiveness and cost benefit analysis tools appear to be common in most road safety investment appraisal models and road safety studies. Nonetheless, these tools are all elaborated as follows.

5.3.1 Cost effectiveness analysis (CEA)

Cost effectiveness is the money spent per reduced crash/casualty (Equation 5.1) and countermeasures with lower cost per crash/casualty are desirable. CEA compares a unit cost of a countermeasure with the non-monetized safety benefits due to its implementation. CEA is a good tool considering a single goal (safety) expressed in either in terms of physical number of lives saved or a reduction of injuries achieved. However, to compare different policy alternatives considering different benefits (safety, environmental and mobility); cost benefit analysis is a more appropriate tool (Wismans, Thynell and Lindberg*,* 2017).

$$\text{Cost effectiveness} = \text{Costs}/\ \text{Crashes prevented} \tag{5.1}$$

5.3.2 Cost utility analysis (CUA)

CUA is a tool used in economic efficiency in which the outcomes of an investment or a programme are expressed in terms of the level of wellbeing of people (Robinson, 1993). The most widely used measure to define the wellbeing of people applied in CUA is the QALY. QALY is a concept which combines the impact of fatalities (assessed by years of life lost) and injuries (assessed by the saved years of living with an injury). In road safety, CUA examines the effect of a countermeasure on different crash severity levels expressed by the number of QALYs (Daniels and Papadimitriou, 2017). This tool is a variant of cost effectiveness (Drummond *et al.,* 2015) whereby CEA computes the cost per crash or casualty prevented while CUA computes cost per QALY (combination of fatalities and different injury severities) (Equation 5.2).

$$\text{Cost utility} = \text{Costs}/\text{QALY} \tag{5.2}$$

5.3.3 Cost benefit analysis (CBA)

CBA is a very widely used economic analysis tool applied to policies, projects, programmes and interventions in road safety. This tool determines the policy priorities and resource allocation typically through safety benefits expressed in terms of reduced number of crashes or casualties. In simple terms, CBA is a process used to estimate the costs and benefits of decisions to find the most cost-effective alternative. In CBA, the costs of countermeasures and their monetized safety benefits determine the BCR (Equation 5.3) and NPV of the investment (Equation 5.4)

$$\text{BCR} = \text{Benefits}/\text{Costs} \tag{5.3}$$

$$\text{NPV} = \text{Benefits} - \text{Costs} \tag{5.4}$$

A countermeasure is economically justified if its BCR is greater than 1.0 and its NPV a positive value. However, there are challenges regarding computation of life cycle costs and benefits of countermeasures as well as crash or casualty unit costs. As an example, costs of countermeasures are generally unknown with most estimates excluding maintenance or overhead costs (Daniels *et al*., 2019). Similarly, the effectiveness of a particular countermeasure is rarely known since it may depend on other factors such as type of the road (urban or rural) and existence of other road safety measures such as campaigns and enforcement (Daniels *et al.,* 2019).

Hauer (2011) describes the CBA tool as deficient due to uncertainties in defining the VOSL used. However, PIARC (2021) and over 80% of the American Association of State Highways and Transportation Officials (AASHTO) member states (McNeil, Tischer and DeBlasio, 2000) typically accept and use CBA as an economic evaluation tool. Road safety analysts prefer this tool due to its ability to provide a complete assessment of all possible objectives (safety, mobility and environment). In some cases, there are additional impacts of road safety measures such as reduced travel time, fuel use and emissions that should be included in a CBA (EC, 2018; OECD/ITF, 2015; SWOV, 2011). In most CBA studies of road safety countermeasures, the direct safety benefits of countermeasure implementation considered are usually expressed in terms of reduced number of crashes or injuries (Daniels *et al.,* 2019; iRAP, 2015a; Harwood *et al.,* 2010; Lawrence *et al.,* 2018). Therefore, the performance of the CBA tool depends on the parameters used and their estimation.

5.4 Economic optimisation techniques

Infrastructure related safety intervention programmes are usually capital intensive requiring tactical planning and management. Road authorities have to make decisions regarding allocation of safety budget among different road safety interventions. Under a constrained budget, selecting countermeasures based on descending order of BCR until the budget is exhausted may not yield sustainable and optimal results (Jiang and Sinha, 1990) since it doesn't offer the flexibility in maximising the available resources or benefits. Generally, the use of the above economic efficiency tools provides some useful information towards making these important decisions (Persaud and Kazakov, 1994) but are not appropriate and effective in budget allocation problems.

Consequently, the ineffectiveness of these tools has led to the growth of optimisation tools. Optimisation also known as mathematical programming is a technique that applies mathematical principles and methods to solve quantitative problems in many fields including physics, biology, engineering, economics and business. Optimisation techniques have been widely applied for over 30 years to allocate resources in road safety programmes. According to Brown (2000), economic optimisation is the systematic evaluation of alternative activities to achieve optimal performance and maximise benefit or income. In this research, economic optimisation refers to the economic appraisal of infrastructure countermeasures to maximise economic safety benefits and improve the effectiveness of road network safety investment programmes. Using optimisation, decision makers are able to make optimal decisions on how to use the limited resources while maximising efficiency. Optimisation techniques determine the most cost-effective set of improvement projects within a fixed budget and other constraints.

Nonetheless, it appears the previous developed optimisation models (Melachrinoudis and Kozanidis, 2002; Mishra and Khasnabis, 2012; Saha and Ksaibati, 2016) have not addressed the biggest challenge of obtaining the best mix or integration between different countermeasures. These models do not distinguish between capital and maintenance countermeasures during the prioritisation process thus resulting in unbiased selection. It is worthwhile to address this challenge faced by road safety analysts and economists so as to improve the effectiveness and sustainability of road safety investment programmes. Therefore, in this Thesis, a new approach of prioritising road safety infrastructure countermeasures taking into consideration their life span is examined and applied to case studies to draw some meaningful conclusions.

5.5 Economic analysis approaches of safety infrastructure measures

To compute the safety benefits due to implementation of road safety countermeasures, it seems necessary to consider the distinction between crashes and casualties. For instance, SafetyAnalyst (Harwood *et al*., 2010) and BCA by FHWA (2018) presented in Chapter 3 are crash-based evaluation models while iRAP (iRAP, 2015) is a casualty-based model. Moreover, E^3 model conducts economic analysis for both crashes and casualties (Martensen and Lassare, 2017). Harmon *et al*. (2018) recommends analysts to work with crashes and crash unit costs during economic appraisal of safety countermeasures. Similarly, in a report by OECD/ITF (2015), the efficiency assessment of a safety related measure requires the number of road crashes or accidents affected by a measure. For PIARC (2020), the key measure to assess effectiveness of any safety infrastructure intervention is the expected reduction in crashes expressed as a crash modification factor (CMF). However, Martensen *et al.* (2016) considers the effectiveness of a measure as a reduction in either the number of crashes or the number of casualties. Also, Wegman (2017) acknowledges all metrics of measuring progress in road safety i.e., the number of road casualties and the associated negative consequences.

In order to perform a CBA all relevant effects of the measure relating to safety, mobility (travel and vehicle expenses) and environment are paramount. However, the effects on mobility and environment appear complex to estimate and are scarce in the scholarly literature. Consequently, most of the appraisal models like SafetyAnalyst and iRAP ignore such effects in their economic analysis except the BCA model that estimates these effects based on reduced number of crashes. Therefore, in the advancement of economic analysis of road safety countermeasures, in order to utilise the available research with regard to mobility and environment, it is imperative that analysts develop or modify their models to analyse crash numbers instead of casualties.

In conclusion, this Thesis conducted an investigation to substantiate the use of crash and casualty numbers during the appraisal process so as to recommend the most appropriate and advantageous approach to road safety analysts and economists.

5.6 Summary

In road safety management, economic analysis of road safety interventions is one of the key elements of a road safety programme aimed at determining accurately the economic benefits. The importance of economic analysis lies in knowing that every country has a limited road safety budget and financial constraints are difficult to overcome, so selection of the most cost-effective safety policies delivering optimal safety outcomes for the lowest cost are necessary. The key components during appraisal of countermeasures are the costs and benefits of infrastructure implementation.

Cost effectiveness, cost utility and cost benefit analyses are some of the tools used to identify the use of scarce resources to obtain the greatest possible benefit or the highest return on investments in road safety. Due to some deficiencies in the above tools coupled with limited road safety budgets, optimisation techniques have been widely applied to help decision makers on how to use the limited resources to maximise efficiency. The next Chapter presents a comparative study of the economic analysis approaches briefly presented in this Chapter.

CHAPTER 6: CRASH VERSUS CASUALTY ECONOMIC ANALYSIS

6.1 Introduction

This Chapter compares a crash and casualty economic analysis approaches of road safety infrastructure measures identified in the previous Chapter. Arguably, economic analysis is one of the key components of the road safety management process that compares benefits and costs associated with investments in road safety infrastructure countermeasures. Unfortunately, crash and casualty-based economic analysis approaches appear to be widely used in the appraisal of infrastructure countermeasures with little consideration of the likely impact of either on the calculated economic benefits and ultimately the selection of countermeasures. The economic implications might be substantial if for instance instead of analysing crashes, casualties are analysed and a significant proportion of crashes not involving casualties are not considered. For instance, in Germany and Finland, PDO crashes have a share of up to 50% in total costs for road crashes. Furthermore, in the analysis conducted for countries that include all severity levels, PDO crashes accounted for 2% to 55% share in the total cost of crashes, which is higher than that of slight injuries ranging between 1.9% and 34% (Wijnen *et al.*, 2017). While the research community to some extent acknowledges the use of these two approaches, no research to date has been conducted to give clarification and guidance on this important stage of the road safety management process.

Consequently, a comparative study in this Chapter was conducted to inform economists and road safety analysts on the most appropriate approach. The other key objective of this study was to inform the subsequent model development so as to embed in the most effective approach to compute economic benefits of infrastructure countermeasures.

As a first step, this Chapter provides a distinction between crashes and casualties. A crash-based approach refers to an economic analysis in which the safety benefits of implementing a countermeasure are the number of crashes reduced or prevented. A road crash or accident refers to unplanned or uncontrolled event involving at least one vehicle, cyclist or motorcyclist and in which at least one person is killed, injured or property is damaged (Ting *et al.,* 2020). Therefore, a crash can be fatal (at least one person is killed), serious (at least one person is seriously injured, and no person killed), slight (at least one person is slightly injured but no person is killed or seriously injured) and finally a PDO crash in which no person is killed nor injured. In a casualty-based approach, the safety benefits of implementing a countermeasure are the number of casualties reduced. A casualty refers to a person killed or injured in a crash (Langford *et al.*, 2004), subdivided into killed, seriously injured and slightly injured. In terms of severity levels, a crash-based approach has more severity levels than a casualty due to the property damage level added that might have a significant effect on the analysis results.

Firstly, this study compares crash and casualty data for 9 European countries to develop some important relationships and conclusions to enhance the economics of road safety infrastructure countermeasures. Based on this comparison, the study critically examines and compares crash and casualty economic analysis approaches.

Furthermore, this study examined the selection of infrastructure measures to prevent crashes versus a casualty-based approach with the view to examine which of the approaches estimates more accurately the benefits of countermeasures within a comprehensive safe road system. To demonstrate the practical differences between these approaches, the study applied case studies taken from iRAP (2021) for the Netherlands and Indonesia analysed using the iRAP methodology and the ViDA software (Hurtado-Beltran, Serna-Rodríguez and Chavez-Cardenas, 2015). Therefore, this Chapter presents the comparative study results and its main findings.

6.2 Methodology and data

To carry out the above analyses, the total cost of crashes and casualties was computed first using the number of crashes/casualties (Table 6-1) from 9 European countries with the respective standard crash and casualty unit costs (Table 6-4) for each severity level and adding them together for each country.

Table 6-1 Crash and casualty data

Country	**Crashes**				**Casualties**		
	Fatal	Serious	Slight	PDO	Fatal	Serious	Slight
Austria	429	9,262	26,917	646,553	523	10,502	34,522
Estonia	61	433	1,345	29,218	67	467	1,756
Finland	208	475	4,641	478,863	229	519	6,186
Germany	3,187	58,744	240,504	2,104,250	3,377	67,732	321,803
Iceland	16	155	741	5,500	16	178	1,130
Ireland	179	398	4,399	21,734	188	508	6,252
Norway	148	597	4,380	403,719	160	693	5,670
Slovenia	112	868	5,605	11,358	120	932	7,778
UK	1,658	20,676	123,988	2,232,305	1,775	22,807	169,895

Source: Wijnen *et al.,* 2017

These unit costs developed by the European SafetyCube project (Thomas *et al.,* 2016) support stakeholders in conducting economic efficiency evaluation of measures. Secondly, to compare the different economic analysis approaches, the study computed a BCR to demonstrate the effect of these approaches on countermeasure selection considering countermeasures with a BCR greater than 3. This selection criteria was chosen by the study to illustrate the difference between the two economic approaches, but as a standard, a recommended minimum of BCR ≥ 1 would suffice (Daniels *et al.,* 2019; iRAP, 2019; Schultz *et al*., 2011). In computing the BCR ratios (Equation 6.1), the study used countermeasure costs for implementation and the monetised safety benefits.

$$\text{BCR} = \text{Benefits}/\text{Countermeasure costs} \qquad (6.1)$$

where;

$$\text{Benefits} = \sum\nolimits_{s} \text{Crashes/Casualties} * \text{Unit costs}_{s} \qquad (6.2)$$

Where; s = severity level.

The monetary safety benefits are the number of crashes/casualties reduced multiplied with the respective unit costs and added together for all the severity levels (Equation 6.2). This research conducted the comparative study between crash and casualty economic analysis approaches using data for the 20-year infrastructure improvement programmes termed as SRIP for the Netherlands and Indonesia.

A SRIP is a summary that shows the total number of fatal and serious injuries (FSI) prevented, economic safety benefits, estimated cost of countermeasures, BCR for the entire plan and individual countermeasures to be implemented over the appraisal period. In iRAP's SRIP, the FSI prevented depend on the risk factors or CMFs of the implemented countermeasures that change the star rating score for the 100m road segments. This FSI data in the SRIP was split to estimate the number of fatalities, injuries and the number of crashes for all severity levels using the ratios (Table 6-2 and Table 6-3) developed from real crash and casualty data (Table 6-1).

Table 6-2 Relationship between crash and casualty severity levels

Crash	Casualties		
	Fatalities	Serious injuries	Slight injuries
Fatal	1.08	-	-
Serious injury	-	1.14	-
Slight injury	-	-	1.35

Table 6-3 Relationship between casualty severity levels

Casualties		
Fatality	Serious injuries	Slight injuries
1	7	45

The ratios in Table 6-2 are comparable to the number of casualties per crash by severity level in Greece and Norway (Wijnen *et al.,* 2017) and those used in other countries and studies to estimate the number of crashes (De Brabander and Veereck, 2007; Wijnen, 2020). As an example, from Table 6-2, on average there are 1.08 fatalities per fatal crash. The total FSI as per iRAP was split considering 7 serious injuries per fatality (Table 6-3) which is lower than the 10 serious injuries per fatality used in iRAP (iRAP, 2015). Therefore, the splitting of FSI conducted by this research appears conservative. The PDO crashes are 88.7% of the total crashes using data in Table 6-1 and this determined the number of PDO crashes in the crash-based approach. Therefore, in this study for every injury, there are approximately 6 PDO crashes, which is comparable to the recommended 6 PDO crashes in urban areas and 5.3 PDO crashes established in South Africa (Luathep and Tanaboriboon, 2005).

6.2.1 Netherlands data

In the Netherlands case study, an infrastructure improvement programme (Table 6-6) obtained from iRAP (2021) and developed using EuroRAP methodology was used.

The economic safety benefits were computed using the number of crashes/casualties prevented together with the respective standard crash and casualty unit costs (Table 6-4) as per Equation 6.2. Consequently, the BCR ratios were computed using the economic benefits computed above and the countermeasure costs (Table 6-6) using Equation 6.1.

Table 6-4 Standard crash and casualty unit costs

Severity level	Crash unit cost (€)	Casualty unit cost (€)
Fatal	2,579,090	2,269,346
Serious	350,797	303,130
Slight	37,340	27,417
PDO	3,959	-

Source: Wijnen *et al.,* 2017

6.2.2 Indonesia data

In this case study, an infrastructure improvement programme (Table 6-7) obtained from iRAP (2021) and developed using iRAP methodology was used. Computation for economic benefits were made using the number of crashes/casualties prevented together with the respective 2018 crash and casualty unit costs (Table 6-5). The 2015-unit costs by Sugiyanto and Santi (2017) were converted to 2018 dollars (Statista, 2022). Equally, countermeasure costs in Table 6-7 were converted to the 2018 dollars before computation of BCR ratios. Equations 6.1 and 6.2 were used to compute the BCR ratios and economic safety benefits respectively.

Table 6-5 Crash and casualty unit costs (Indonesia)

Severity level	2015 Unit costs ($)		2018 Unit costs ($)	
	Crash	Casualty	Crash	Casualty
Fatal	40,144	37,168	42,151	39,026
Severe	2,104	1,400	2,209	1,470
Minor/Slight	878	464	922	487
PDO	296	-	311	-

Source: Sugiyanto and Santi, 2017

Table 6-6 Infrastructure improvement programme (Netherlands)

S/N	Countermeasure	Length / Sites	Fatalities & serious injuries saved	Present value of safety benefit (€)	Estimated Cost (€)	Program BCR
1	Signalised crossing	1 sites	10	3,233,649	45,000	72
2	Improve curve delineation	0.40 km	0.5	148,419	7,460	20
3	Sight distance (obstruction removal)	1.40 km	2	678,298	35,280	19
4	Pedestrian fencing	27.20 km	9	2,976,955	179,606	17
5	Street lighting (intersection)	14 sites	21	6,599,575	504,000	13
6	Refuge Island	14 sites	14	4,606,949	416,422	11
7	Shoulder rumble strips	199.30 km	84	27,156,276	2,382,592	11
8	Protected turn lane (unsignalised 4 leg)	3 sites	14	4,375,323	535,399	8
9	Unsignalised crossing	5 sites	4	1,230,100	217,465	6
10	Centreline rumble strip / flexi-post	1.80 km	0.3	108,423	19,512	6
11	Central hatching	5.70 km	0.6	184,481	34,173	5
12	Parking improvements	1.50 km	0.3	99,666	18,900	5
13	Improve Delineation	45.70 km	13	4,190,892	847,446	5
14	Traffic calming	2.90 km	1	370,148	87,581	4
15	Central median barrier (no duplication)	0.70 km	1	365,701	95,182	4
16	Protected turn lane (unsignalised 3 leg)	54 sites	74	23,918,473	7,210,571	3
17	Footpath provision driver side (adjacent to road)	27.90 km	35	11,319,681	4,388,280	3
18	Footpath provision passenger side (>3m from road)	26.80 km	29	9,267,974	3,085,368	3
19	Footpath provision driver side (>3m from road)	25.40 km	28	9,060,036	2,922,040	3
20	Bicycle Lane (off-road)	3.50 km	3	1,122,681	392,156	3
21	Footpath provision passenger side (informal path >1m)	5.80 km	1	406,768	141,451	3
22	Footpath provision driver side (informal path >1m)	4.70 km	1	307,139	114,747	3
23	Roadside barriers - driver side	206.20 km	199	64,041,774	27,898,500	2
24	Roadside barriers - passenger side	159.20 km	111	35,791,424	21,558,000	2
25	Footpath provision passenger side (adjacent to road)	44.10 km	52	16,843,531	6,939,120	2
26	Central median barrier (1+1)	34.80 km	41	13,286,137	6,288,200	2
27	Wide centreline	12.50 km	0.6	181,898	75,710	2
28	Delineation and signing (intersection)	8 sites	0.5	149,378	88,582	2
29	Road surface rehabilitation	0.80 km	0.4	115,173	70,435	2
30	Clear roadside hazards - driver side	0.10 km	0.1	34,232	20,000	2
31	Additional lane (2 + 1 road with barrier)	15.10 km	80	25,660,031	20,655,000	1
32	Shoulder sealing driver side (>1m)	103.50 km	40	12,712,184	9,156,140	1
33	Shoulder sealing passenger side (>1m)	71.50 km	29	9,428,574	6,334,720	1
34	Duplication with median barrier	1.20 km	26	8,323,159	6,480,000	1
35	Street lighting (mid-block)	10.30 km	4	1,352,702	1,483,200	1
36	Upgrade pedestrian facility quality	43 sites	3	826,756	767,405	1
37	Lane widening (up to 0.5m)	1.00 km	2	684,333	656,756	1
38	Overtaking lane	0.30 km	1	339,394	405,000	1
39	Shoulder sealing passenger side (<1m)	6.60 km	0.9	292,349	294,490	1
40	Protected turn provision at existing signalised site (4-leg)	1 sites	0.6	204,497	237,955	1
41	Lane widening (>0.5m)	0.10 km	0.6	186,272	152,529	1
42	Clear roadside hazards (bike lane)	1.20 km	0.5	160,633	216,000	1
43	Shoulder sealing driver side (<1m)	1.50 km	0.2	68,926	66,640	1
44	Side road signalised pedestrian crossing	1 sites	0.1	28,480	45,000	1
45	Street lighting (ped crossing)	2 sites	0.1	26,839	36,000	1

Source: iRAP, 2021

Table 6-7 Infrastructure improvement programme (Indonesia)

S/N	Countermeasure	Length/Sites	Fatalities and serious injuries saved	Present value of safety benefits (Rp IDR)	Estimated cost (Rp IDR)	Program BCR
1	Centreline rumble strip / flexi-post	0.20 km	3	1,174,737,174	24,388,503	48
2	Central hatching	10.30 km	55	25,379,675,917	628,003,941	40
3	Implement one way network	8.70 km	509	235,843,048,500	8,916,804,000	26
4	Sight distance (obstruction removal)	0.90 km	14	6,497,673,481	365,827,539	18
5	Shoulder rumble strips	1.60 km	3	1,580,203,577	130,072,014	12
6	Clear roadside hazards (bike lane)	1.30 km	2	996,279,612	92,000,000	11
7	Pave road surface	1.40 km	32	14,611,773,378	1,580,736,278	9
8	Upgrade pedestrian facility quality	15 sites	2	1,133,084,485	203,237,521	6
9	Central median barrier (no duplication)	0.40 km	2	892,706,606	177,652,800	5
10	Improve curve delineation	2.00 km	23	10,639,367,658	2,196,422,135	5
11	Improve Delineation	8.70 km	20	9,166,268,328	1,823,444,791	5
12	Refuge Island	63 sites	24	11,172,101,771	2,560,792,770	4
13	Unsignalised crossing	11 sites	4	1,975,586,578	447,122,547	4
14	Central turning lane full length	0.60 km	10	4,633,754,813	1,586,367,884	3
15	Delineation and signing (intersection)	17 sites	12	5,622,018,563	1,768,007,718	3
16	Footpath provision passenger side (>3m from road)	8.20 km	52	23,916,518,559	9,350,723,335	3
17	Overtaking lane	8.40 km	104	48,043,039,199	17,218,656,000	3
18	Pedestrian fencing	8.10 km	33	15,162,427,589	5,670,000,000	3
19	Signalise intersection (4-leg)	11 sites	44	20,369,120,333	6,149,520,000	3
20	Skid Resistance (paved road)	0.90 km	24	10,940,669,516	3,793,767,067	3
21	Bicycle Lane (on-road)	3.50 km	0.8	371,144,825	154,506,690	2
22	Footpath provision driver side (>3m from road)	21.00 km	99	45,900,138,474	23,946,974,394	2
23	Footpath provision passenger side (adjacent to road)	1.50 km	6	2,557,896,148	1,500,498,171	2
24	Motorcycle Lane (Segregated)	1.60 km	7	3,120,444,483	1,758,441,177	2
25	Parking improvements	8.20 km	31	14,458,247,767	9,104,706,000	2
26	Protected turn provision at existing signalised site (3-leg)	4 sites	5	2,530,857,675	1,639,872,000	2
27	Protected turn provision at existing signalised site (4-leg)	26 sites	42	19,459,807,115	10,659,168,000	2
28	Road surface rehabilitation	1.20 km	7	3,122,279,257	1,951,080,206	2
29	School zone - crossing guard or supervisor	24 sites	9	4,129,041,964	2,007,786,446	2
30	School zone warning - signs and markings	0.80 km	0.4	178,923,798	99,460,625	2
31	Shoulder sealing driver side (>1m)	0.30 km	0.5	219,939,931	108,520,941	2
32	Signalise intersection (3-leg)	47 sites	113	52,485,207,568	23,983,128,000	2
33	Street lighting (mid-block)	1.70 km	7	3,438,176,085	1,475,322,132	2
34	Traffic calming	25.40 km	259	119,857,492,155	50,367,180,314	2
35	Bicycle Lane (off-road)	0.70 km	1	563,729,844	581,362,185	1
36	Clear roadside hazards - driver side	4.20 km	27	12,554,788,100	10,761,660,000	1
37	Clear roadside hazards - passenger side	4.80 km	32	14,973,443,146	12,299,040,000	1
38	Footpath provision driver side (adjacent to road)	0.30 km	0.9	434,712,034	300,099,634	1
39	Protected turn lane (unsignalised 4 leg)	2 sites	2	778,522,810	819,936,000	1
40	Roadside barriers - passenger side	0.10 km	0.5	216,203,400	275,222,994	1
41	School zone warning - flashing beacon	17 sites	2	1,029,414,644	850,000,000	1
42	Side road unsignalised pedestrian crossing	16 sites	1	609,488,233	650,360,069	1
43	Signalised crossing	35 sites	22	10,332,118,438	11,376,612,000	1
44	Street lighting (ped crossing)	3 sites	0.6	257,180,898	317,273,577	1

Source: iRAP, 2021

6.3 Results

6.3.1 Comparing the total cost of crashes and casualties

Table 6-8 presents the total cost of crashes/casualties in each country computed by multiplying the number of crashes/casualties together with the respective unit costs in Table 6-4. Considering all the severity levels for crashes/casualties, on average, the total cost of crashes is higher by over 70% compared to the total cost of casualties. There are two possible explanations for these results. It may be observed that in the cost for crashes, four severity levels are considered including a PDO level that is excluded in the cost for casualties. In addition, the unit cost per crash severity level is higher than the corresponding casualty severity level despite the high number of casualties.

Table 6-8 Comparing the cost of crashes and casualties

Country	Crashes					Casualties			
	Fatal	Serious	Slight	PDO	Total cost of crashes (€)	Fatal	Serious	Slight	Total cost of casualties (€)
Austria	429	9,262	26,917	646,553	7,920,295,531	523	10,502	34,522	5,316,828,892
Estonia	61	433	1,345	29,218	475,115,953	67	467	1,756	341,752,144
Finland	208	475	4,641	478,863	2,772,192,852	229	519	6,186	846,606,266
Germany	3,187	58,744	240,504	2,104,250	46,137,923,908	3,377	67,732	321,803	37,018,055,453
Iceland	16	155	741	5,500	145,082,415	16	178	1,130	121,247,886
Ireland	179	398	4,399	21,734	851,577,882	188	508	6,252	752,038,172
Norway	148	597	4,380	403,719	2,353,003,850	160	693	5,670	728,618,840
Slovenia	112	868	5,605	11,358	847,606,898	120	932	7,778	768,088,106
UK	1,658	20,676	123,988	2,232,305	24,996,617,407	1,775	22,807	169,895	15,599,586,275

6.3.2 The impact of crash and casualty approaches on countermeasure selection (Netherlands case study)

This section presents the results from the application of the different economic analysis approaches and the resulting impact on countermeasure selection to the Netherlands case study. Specifically, the study critically examines the impact of the iRAP approach and in general the crash and casualty economic analysis approaches on selection of road safety countermeasures.

1. **iRAP approach**

Firstly, this study further analysed the infrastructure improvement programme in Table 6-6 and recomputed the BCR values using the iRAP approach and the standard casualty unit costs (Table 6-4). Therefore, Table 6-9 presents the list of countermeasures selected using the iRAP approach based on the economic selection criteria. It may be noted that the BCR values have changed significantly due to the unit costs and ratios used presented in Table 6-4 and Table 6-3 respectively that differ from those used to compute the BCR values in Table 6-6.

The iRAP model performs economic analysis of single or multiple countermeasures during the preparation of the SRIP (iRAP, 2015). Although iRAP does not consider all the injury severity levels, it is typically a casualty-based model. In this approach, the number of fatalities and serious injuries saved are only considered and this results into the selection of 26 countermeasures (Table 6-9). This approach doesn't include slight injuries in the computation of economic safety benefits, and this majorly distinguishes this approach from a standard casualty based economic analysis approach presented in the next section.

Table 6-9 Measures selected for BCR>3 using the iRAP approach (Netherlands)

S/N	Countermeasure	Length / Sites	Fatalities	Serious injuries	Safety benefit (€)	Estimated Cost (€)	Program BCR
1	Signalised crossing	1 sites	1.3	8.8	5,489,070	45,000	122
2	Improve curve delineation	0.40 km	0.1	0.4	274,454	7,460	37
3	Sight distance (obstruction removal)	1.40 km	0.3	1.8	1,097,814	35,280	31
4	Pedestrian fencing	27.20 km	1.1	7.9	4,940,163	179,606	28
5	Street lighting (intersection)	14 sites	2.6	18.4	11,527,047	504,000	23
6	Shoulder rumble strips	199.30 km	10.5	73.5	46,108,188	2,382,592	19
7	Refuge Island	14 sites	1.8	12.3	7,684,698	416,422	18
8	Protected turn lane (unsignalised 4 leg)	3 sites	1.8	12.3	7,684,698	535,399	14
9	Unsignalised crossing	5 sites	0.5	3.5	2,195,628	217,465	10
10	Central hatching	5.70 km	0.1	0.5	329,344	34,173	10
11	Parking improvements	1.50 km	0.0	0.3	164,672	18,900	9
12	Centreline rumble strip / flexi-post	1.80 km	0.0	0.3	164,672	19,512	8
13	Improve Delineation	45.70 km	1.6	11.4	7,135,791	847,446	8
14	Traffic calming	2.90 km	0.1	0.9	548,907	87,581	6
15	Central median barrier (no duplication)	0.70 km	0.1	0.9	548,907	95,182	6
16	Protected turn lane (unsignalised 3 leg)	54 sites	9.3	64.8	40,619,118	7,210,571	6
17	Footpath provision driver side (>3m from road)	25.40 km	3.5	24.5	15,369,396	2,922,040	5
18	Footpath provision passenger side (>3m from road)	26.80 km	3.6	25.4	15,918,303	3,085,368	5
19	Footpath provision driver side (informal path >1m)	4.70 km	0.1	0.9	548,907	114,747	5
20	Footpath provision driver side (adjacent to road)	27.90 km	4.4	30.6	19,211,745	4,388,280	4
21	Wide centreline	12.50 km	0.1	0.5	329,344	75,710	4
22	Bicycle Lane (off-road)	3.50 km	0.4	2.6	1,646,721	392,156	4
23	Footpath provision passenger side (adjacent to road)	44.10 km	6.5	45.5	28,543,164	6,939,120	4
24	Roadside barriers - driver side	206.20 km	24.9	174.1	109,232,493	27,898,500	4
25	Footpath provision passenger side (informal path >1m)	5.80 km	0.1	0.9	548,907	141,451	4
26	Central median barrier (1+1)	34.80 km	5.1	35.9	22,505,187	6,288,200	4

2. Casualty based economic analysis approach

In this approach, the economic analysis includes fatalities, serious and slight injuries. Consequently, by including the number of slight injuries saved (excluded in the iRAP approach) in the casualty-based approach results in the selection of 30 countermeasures presented in Table 6-10 compared to the 26 countermeasures selected in the iRAP approach. The 4 countermeasures added to Table 6-9 represents an increase of 15% in the number of countermeasures selected compared to the iRAP approach. In addition, the value of safety benefits increases by 28% for each of the countermeasures in the casualty-based approach. For example, the safety benefits of implementing signalised crossings increase from €5.5 million in the iRAP approach to €7.0 million in the casualty-based approach.

Generally, the change in the number of countermeasures selected and safety benefits seems to be significant because slight injuries on average are 85% of the total number of casualties and account for over 20% of the total cost of casualties (Table 6-8) which is between 1.9% and 34% previously established by Wijnen *et al*. (2017). In Great Britain (DfT, 2020), the slight injuries were 79% of the total number of casualties in 2019. This may give an implication, that even in a casualty-based model like iRAP, it is important to consider slight injuries during economic appraisal of countermeasures as they have a significant impact on countermeasure selection.

Table 6-10 Measures selected for BCR>3 using the casualty-based approach (Netherlands)

S/N	Countermeasure	Length / Sites	Fatalities	Serious injuries	Slight injuries	Safety benefit (€)	Estimated Cost (€)	Program BCR
1	Signalised crossing	1 sites	1.3	8.8	56.4	7,035,172	45,000	156
2	Improve curve delineation	0.40 km	0.1	0.4	2.8	351,759	7,460	47
3	Sight distance (obstruction removal)	1.40 km	0.3	1.8	11.3	1,407,034	35,280	40
4	Pedestrian fencing	27.20 km	1.1	7.9	50.8	6,331,655	179,606	35
5	Street lighting (intersection)	14 sites	2.6	18.4	118.4	14,773,861	504,000	29
6	Shoulder rumble strips	199.30 km	10.5	73.5	473.7	59,095,445	2,382,592	25
7	Refuge Island	14 sites	1.8	12.3	78.9	9,849,241	416,422	24
8	Protected turn lane (unsignalised 4 leg)	3 sites	1.8	12.3	78.9	9,849,241	535,399	18
9	Unsignalised crossing	5 sites	0.5	3.5	22.6	2,814,069	217,465	13
10	Central hatching	5.70 km	0.1	0.5	3.4	422,110	34,173	12
11	Parking improvements	1.50 km	0.0	0.3	1.7	211,055	18,900	11
12	Centreline rumble strip / flexi-post	1.80 km	0.0	0.3	1.7	211,055	19,512	11
13	Improve Delineation	45.70 km	1.6	11.4	73.3	9,145,724	847,446	11
14	Traffic calming	2.90 km	0.1	0.9	5.6	703,517	87,581	8
15	Central median barrier (no duplication)	0.70 km	0.1	0.9	5.6	703,517	95,182	7
16	Protected turn lane (unsignalised 3 leg)	54 sites	9.3	64.8	417.3	52,060,273	7,210,571	7
17	Footpath provision driver side (>3m from road)	25.40 km	3.5	24.5	157.9	19,698,482	2,922,040	7
18	Footpath provision passenger side (>3m from road)	26.80 km	3.6	25.4	163.5	20,401,999	3,085,368	7
19	Footpath provision driver side (informal path >1m)	4.70 km	0.1	0.9	5.6	703,517	114,747	6
20	Footpath provision driver side (adjacent to road)	27.90 km	4.4	30.6	197.4	24,623,102	4,388,280	6
21	Wide centreline	12.50 km	0.1	0.5	3.4	422,110	75,710	6
22	Bicycle Lane (off-road)	3.50 km	0.4	2.6	16.9	2,110,552	392,156	5
23	Footpath provision passenger side (adjacent to road)	44.10 km	6.5	45.5	293.2	36,582,894	6,939,120	5
24	Roadside barriers - driver side	206.20 km	24.9	174.1	1122.2	139,999,922	27,898,500	5
25	Footpath provision passenger side (informal path >1m)	5.80 km	0.1	0.9	5.6	703,517	141,451	5
26	Central median barrier (1+1)	34.80 km	5.1	35.9	231.2	28,844,205	6,288,200	5
27	Road surface rehabilitation	0.80 km	0.1	0.4	2.3	281,407	70,435	4
28	Delineation and signing (intersection)	8 sites	0.1	0.4	2.8	351,759	88,582	4
29	Roadside barriers - passenger side	159.20 km	13.9	97.1	626.0	78,090,409	21,558,000	4
30	Clear roadside hazards - driver side	0.10 km	0.0	0.1	0.6	70,352	20,000	4

3. Crash based economic analysis approach

In the crash-based approach, distinct from the above approaches, considers the number of crashes (fatal, serious, slight and PDO) instead of casualties. Consequently, there are 33 countermeasures selected for implementation as presented in Table 6-11 compared to the 30 countermeasures selected in the casualty based approach (Table 6-10). The extra 3 countermeasures added by this approach account for a 10% increase in the number of countermeasures selected compared to the casualty-based approach. In addition, the safety benefits increase by 26% for each of the countermeasures being analysed. For instance, the safety benefits of implementing signalised crossings increase from €7.0 million in the casualty-based approach to €8.8 million in the crash-based approach.

Generally, the results show that a crash-based approach is more effective compared to a casualty-based approach as the BCR threshold values are increased.

Table 6-11 Measures selected for BCR>3 using a crash-based approach (Netherlands)

S/N	Countermeasure	Length / Sites	Fatal	Serious injury	Slight injury	PDO	Safety benefit (€)	Estimated Cost (€)	Program BCR
1	Signalised crossing	1 sites	1.2	7.7	41.9	397.5	8,829,598	45,000	196
2	Improve curve delineation	0.40 km	0.1	0.4	2.1	19.9	441,480	7,460	59
3	Sight distance (obstruction removal)	1.40 km	0.2	1.5	8.4	79.5	1,765,920	35,280	50
4	Pedestrian fencing	27.20 km	1.0	6.9	37.7	357.8	7,946,638	179,606	44
5	Street lighting (intersection)	14 sites	2.4	16.1	88.0	834.8	18,542,156	504,000	37
6	Shoulder rumble strips	199.30 km	9.8	64.5	352.1	3339.4	74,168,624	2,382,592	31
7	Refuge Island	14 sites	1.6	10.8	58.7	556.6	12,361,437	416,422	30
8	Protected turn lane (unsignalised 4 leg)	3 sites	1.6	10.8	58.7	556.6	12,361,437	535,399	23
9	Unsignalised crossing	5 sites	0.5	3.1	16.8	159.0	3,531,839	217,465	16
10	Central hatching	5.70 km	0.1	0.5	2.5	23.9	529,776	34,173	16
11	Parking improvements	1.50 km	0.0	0.2	1.3	11.9	264,888	18,900	14
12	Centreline rumble strip / flexi-post	1.80 km	0.0	0.2	1.3	11.9	264,888	19,512	14
13	Improve Delineation	45.70 km	1.5	10.0	54.5	516.8	11,478,478	847,446	14
14	Traffic calming	2.90 km	0.1	0.8	4.2	39.8	882,960	87,581	10
15	Central median barrier (no duplication)	0.70 km	0.1	0.8	4.2	39.8	882,960	95,182	9
16	Protected turn lane (unsignalised 3 leg)	54 sites	8.6	56.9	310.2	2941.8	65,339,026	7,210,571	9
17	Footpath provision driver side (>3m from road)	25.40 km	3.3	21.5	117.4	1113.1	24,722,875	2,922,040	8
18	Footpath provision passenger side (>3m from road)	26.80 km	3.4	22.3	121.6	1152.9	25,605,835	3,085,368	8
19	Footpath provision driver side (informal path >1m)	4.70 km	0.1	0.8	4.2	39.8	882,960	114,747	8
20	Footpath provision driver side (adjacent to road)	27.90 km	4.1	26.9	146.7	1391.4	30,903,593	4,388,280	7
21	Wide centreline	12.50 km	0.1	0.5	2.5	23.9	529,776	75,710	7
22	Bicycle Lane (off-road)	3.50 km	0.3	2.3	12.6	119.3	2,648,879	392,156	7
23	Footpath provision passenger side (adjacent to road)	44.10 km	6.0	39.9	218.0	2067.2	45,913,910	6,939,120	7
24	Roadside barriers - driver side	206.20 km	23.1	152.9	834.1	7911.1	175,709,003	27,898,500	6
25	Footpath provision passenger side (informal path >1m)	5.80 km	0.1	0.8	4.2	39.8	882,960	141,451	6
26	Central median barrier (1+1)	34.80 km	4.8	31.5	171.9	1629.9	36,201,352	6,288,200	6
27	Road surface rehabilitation	0.80 km	0.0	0.3	1.7	15.9	353,184	70,435	5
28	Delineation and signing (intersection)	8 sites	0.1	0.4	2.1	19.9	441,480	88,582	5
29	Roadside barriers - passenger side	159.20 km	12.9	85.3	465.3	4412.7	98,008,539	21,558,000	5
30	Clear roadside hazards - driver side	0.10 km	0.0	0.1	0.4	4.0	88,296	20,000	4
31	Shoulder sealing passenger side (>1m)	71.50 km	3.4	22.3	121.6	1152.9	25,605,835	6,334,720	4
32	Shoulder sealing driver side (>1m)	103.50 km	4.6	30.7	167.7	1590.2	35,318,393	9,156,140	4
33	Duplication with median barrier	1.20 km	3.0	20.0	109.0	1033.6	22,956,955	6,480,000	4

This may explain why road safety economists should ideally work with crashes and not casualties as previously recommended by Harmon *et al.* (2018). The increase is justified partly by the large number of PDO crashes, which on average are 90% of the total crashes (Table 6-8) which is comparable to 88.3% established on the network of Korean expressways in 2008 by Park *et al.* (2012). Therefore, in a casualty-based approach, there is a likelihood of a good number of crashes not considered that may not result in any casualty as seen above. The difference in unit costs together with the number of PDO crashes have a much higher impact on the economic analysis results. This supports the previous argument by Wijnen *et al.* (2017) where the PDO crashes are major cost components in most countries and their exclusion might result in underestimation of total cost of crashes. This impact is cumulative with more severity levels considered and becomes substantial with the addition of PDO crashes, which are usually more than the other severity levels.

The implementation of a particular measure may have differing effects depending on the severity level, which is important in any evaluation. It is important at this stage to remember that most infrastructure measures are designed based on an analysis of crash data and accident causation and not on casualties' causation thus leading to countermeasure effectiveness often expressed in terms of a crash reduction and not a casualty reduction, hence the common term CMF. In addition, to facilitate international comparison and standardise accident data collection, economic analysis of countermeasures must also be standardised and streamlined with regard to the crash-based approach.

The analysis above is a specific case study used as a demonstrator of the need to consider crash-based costs instead of casualty-based costs and without examining whether there are constraints in the road safety budget. In addition, the overall countermeasures prioritisation procedure requires examination with regard to the existing road conditions together with the selection and prioritisation mechanism. For example, it is important to group the countermeasures with regard to their frequency of implementation and the budget source. In other words, distinction is required of the above countermeasures as routine, periodic or rehabilitation works. This may have a significant impact on the final selection of countermeasures together with any budget constraints of the agency responsible for implementing the above countermeasures programme (Azmi and Evdorides, 2019).

6.3.3 The impact of crash and casualty approaches on countermeasure selection (Indonesia case study)

The application of the economic analysis approaches applied in the Netherlands case study are equally applied to this case study and the results are presented in this section. Another case study was chosen by this research to compare results from different case studies particularly from a developed and a developing country so as to draw firm conclusions from the study. However, as may be seen in this section, fewer measures are selected in all approaches (for BCR>3) in this case study because the economic benefits due to implementation of countermeasures are much lower compared to those in the Netherlands case study. This may be explained by the high crash/casualty unit costs used in the Netherlands case study which are incomparable to those used in the Indonesia case study.

1. iRAP approach

The results for the iRAP approach (considering fatalities and serious injuries only) show that 3 countermeasures (Table 6-12) are selected for implementation with the given economic selection criteria (BCR>3). To elaborate further the impact of crash and casualty based economic analysis approaches on countermeasure selection; a minimum economic criterion of BCR ≥1 was applied to this case study. In economic appraisal of infrastructure measures, countermeasures are usually economically justified if their BCR ≥ 1 (Daniels *et al.,* 2019; iRAP, 2019; Schultz *et al*., 2011) considering the BCR as the economic selection criteria. Therefore, applying this minimum economic selection criteria (BCR ≥ 1) results in selection of 19 countermeasures (Table 6-13). It may be seen that more countermeasures are selected due to the application of a lower economic selection criteria.

Table 6-12 Measures selected for BCR>3 using the iRAP approach (Indonesia)

S/N	Countermeasure	Length/Sites	Fatalities	Serious injuries	Safety benefit ($)	Estimated cost ($)	Program BCR
1	Centreline rumble strip / flexi-post	0.20 km	0.4	2.6	18,494	1,684	11
2	Central hatching	10.30 km	6.9	48.1	339,050	43,367	8
3	Implement one way network	8.70 km	63.6	445.4	3,137,756	615,759	5

Table 6-13 Measures selected for BCR≥1 using the iRAP approach (Indonesia)

S/N	Countermeasure	Length/Sites	Fatalities	Serious injuries	Safety benefit ($)	Estimated cost ($)	Program BCR
1	Centreline rumble strip / flexi-post	0.20 km	0.4	2.6	18,494	1,684	11
2	Central hatching	10.30 km	6.9	48.1	339,050	43,367	8
3	Implement one way network	8.70 km	63.6	445.4	3,137,756	615,759	5
4	Sight distance (obstruction removal)	0.90 km	1.8	12.3	86,304	25,263	3
5	Shoulder rumble strips	1.60 km	0.4	2.6	18,494	8,982	2
6	Clear roadside hazards (bike lane)	1.30 km	0.3	1.8	12,329	6,353	2
7	Pave road surface	1.40 km	4.0	28.0	197,266	109,159	2
8	Central median barrier (no duplication)	0.40 km	0.3	1.8	12,329	12,268	1
9	Improve Delineation	8.70 km	2.5	17.5	123,291	125,920	1
10	Improve curve delineation	2.00 km	2.9	20.1	141,785	151,676	1
11	Upgrade pedestrian facility quality	15 sites	0.3	1.8	12,329	14,035	1
12	Refuge Island	63 sites	3.0	21.0	147,949	176,838	1
13	Unsignalised crossing	11 sites	0.5	3.5	24,658	30,876	1
14	Signalise intersection (4-leg)	11 sites	5.5	38.5	271,240	424,661	1
15	Delineation and signing (intersection)	17 sites	1.5	10.5	73,975	122,092	1
16	Skid Resistance (paved road)	0.90 km	3.0	21.0	147,949	261,982	1
17	Central turning lane full length	0.60 km	1.3	8.8	61,646	109,548	1
18	Overtaking lane	8.40 km	13.0	91.0	641,113	1,189,052	1
19	Pedestrian fencing	8.10 km	4.1	28.9	203,430	391,548	1

2. Casualty based economic analysis approach

In the casualty based economic analysis approach that considers 3 severity levels (fatalities, serious and slight injuries), 4 countermeasures are selected (Table 6-14). The economic safety benefits of countermeasure implementation increase by 45% compared to the iRAP approach. As an example, the monetised safety benefits for implementing a central hatching countermeasure increase from $339,050 to $490,158. In this case, the countermeasure selection increases by over 30% due to the change from the iRAP approach to the casualty based economic analysis approach.

Table 6-14 Measures selected for BCR>3 using casualty-based approach (Indonesia)

S/N	Countermeasure	Length/Sites	Fatalities	Serious injuries	Slight injuries	Safety benefit ($)	Estimated cost ($)	Program BCR
1	Centreline rumble strip / flexi-post	0.20 km	0.4	2.6	16.9	26,736	1,684	16
2	Central hatching	10.30 km	6.9	48.1	310.2	490,158	43,367	11
3	Implement one way network	8.70 km	63.6	445.4	2870.4	4,536,194	615,759	7
4	Sight distance (obstruction removal)	0.90 km	1.8	12.3	78.9	124,768	25,263	5

A possible explanation for this change may be due to the addition of slight injuries in the computation of economic benefits. This may imply that selection of countermeasures may significantly change depending on the chosen threshold BCR value due to increase in economic benefits. Arguably, if the analysis does not include slight injuries, a good number of measures may not be economically justified whereas in reality they are economically sound. As an example, in this case study, 19 countermeasures (Table 6-13) are selected considering countermeasures with BCR ≥ 1 in the iRAP approach compared to 31 countermeasures (Table 6-15) in the casualty-based approach. This represents an increase in countermeasure selection of over 60% doubling the 30% increase obtained using the previous economic selection criteria of BCR > 3. Comparing with the iRAP approach, 12 countermeasures are added in this casualty based economic analysis approach.

The addition of slight injuries in the casualty approach makes them meet the economic selection criteria due to increased economic safety benefits. According to the crash/casualty data analysed by this research, 85% of the total casualties are slight injuries and these account for over 20% of the total cost of casualties. This is comparable to the 87% of the total number of casualties and 23% of the total cost of casualties established in the UK in 2003 by Morris *et al*. (2006). Therefore, a casualty approach is superior to the iRAP approach and thus it is important that computation of safety benefits includes slight injuries in economic appraisal of road safety countermeasures.

Table 6-15 Measures selected for BCR≥1 using casualty-based approach (Indonesia)

S/N	Countermeasure	Length/Sites	Fatalities	Serious injuries	Slight injuries	Safety benefit ($)	Estimated cost ($)	Program BCR
1	Centreline rumble strip / flexi-post	0.20 km	0.4	2.6	16.9	26,736	1,684	16
2	Central hatching	10.30 km	6.9	48.1	310.2	490,158	43,367	11
3	Implement one way network	8.70 km	63.6	445.4	2870.4	4,536,194	615,759	7
4	Sight distance (obstruction removal)	0.90 km	1.8	12.3	78.9	124,768	25,263	5
5	Shoulder rumble strips	1.60 km	0.4	2.6	16.9	26,736	8,982	3
6	Clear roadside hazards (bike lane)	1.30 km	0.3	1.8	11.3	17,824	6,353	3
7	Pave road surface	1.40 km	4.0	28.0	180.5	285,183	109,159	3
8	Central median barrier (no duplication)	0.40 km	0.3	1.8	11.3	17,824	12,268	1
9	Improve Delineation	8.70 km	2.5	17.5	112.8	178,239	125,920	1
10	Improve curve delineation	2.00 km	2.9	20.1	129.7	204,975	151,676	1
11	Upgrade pedestrian facility quality	15 sites	0.3	1.8	11.3	17,824	14,035	1
12	Refuge Island	63 sites	3.0	21.0	135.3	213,887	176,838	1
13	Unsignalised crossing	11 sites	0.5	3.5	22.6	35,648	30,876	1
14	Signalise intersection (4-leg)	11 sites	5.5	38.5	248.1	392,127	424,661	1
15	Delineation and signing (intersection)	17 sites	1.5	10.5	67.7	106,944	122,092	1
16	Skid Resistance (paved road)	0.90 km	3.0	21.0	135.3	213,887	261,982	1
17	Central turning lane full length	0.60 km	1.3	8.8	56.4	89,120	109,548	1
18	Overtaking lane	8.40 km	13.0	91.0	586.5	926,845	1,189,052	1
19	Pedestrian fencing	8.10 km	4.1	28.9	186.1	294,095	391,548	1
20	Footpath provision passenger side (>3m from road)	8.20 km	6.5	45.5	293.2	463,423	645,724	1
21	Bicycle Lane (on-road)	3.50 km	0.1	0.7	4.5	7,130	10,670	1
22	Traffic calming	25.40 km	32.4	226.6	1460.6	2,308,201	3,478,156	1
23	Street lighting (mid-block)	1.70 km	0.9	6.1	39.5	62,384	101,880	1
24	Signalise intersection (3-leg)	47 sites	14.1	98.9	637.2	1,007,053	1,656,179	1
25	Shoulder sealing driver side (>1m)	0.30 km	0.1	0.4	2.8	4,456	7,494	1
26	School zone - crossing guard or supervisor	24 sites	1.1	7.9	50.8	80,208	138,650	1
27	Footpath provision driver side (>3m from road)	21.00 km	12.4	86.6	558.3	882,285	1,653,682	1
28	School zone warning - signs and markings	0.80 km	0.1	0.4	2.3	3,565	6,868	1
29	Footpath provision passenger side (adjacent to road)	1.50 km	0.8	5.3	33.8	53,472	103,618	1
30	Motorcycle Lane (Segregated)	1.60 km	0.9	6.1	39.5	62,384	121,431	1
31	Protected turn provision at existing signalised site (4-leg)	26 sites	5.3	36.8	236.8	374,303	736,080	1

3. Crash based economic analysis approach

In the crash based economic analysis approach, 9 countermeasures (Table 6-16) meet the criteria for selection (BCR>3). In this approach, there are more 5 countermeasures added in the selection compared to the casualty-based approach due to an increase in economic benefits by 156%. For instance, the economic safety benefits for implementing a central hatching measure increase from $490,158 to $1,254,710.

Table 6-16 Countermeasures selected for BCR>3 using crash-based approach (Indonesia)

S/N	Countermeasure	Length/Sites	Fatal	Serious injury	Slight injury	PDO	Safety benefit ($)	Estimated cost ($)	Program BCR
1	Centreline rumble strip / flexi-post	0.20 km	0.3	2.3	12.6	119.3	68,439	1,684	41
2	Central hatching	10.30 km	6.4	42.3	230.5	2186.5	1,254,710	43,367	29
3	Implement one way network	8.70 km	59.1	391.0	2133.5	20234.9	11,611,770	615,759	19
4	Sight distance (obstruction removal)	0.90 km	1.63	10.8	58.7	556.6	319,381	25,263	13
5	Shoulder rumble strips	1.60 km	0.35	2.3	12.6	119.3	68,439	8,982	8
6	Clear roadside hazards (bike lane)	1.30 km	0.2	1.5	8.4	79.5	45,626	6,353	7
7	Pave road surface	1.40 km	3.72	24.6	134.1	1272.1	730,013	109,159	7
8	Central median barrier (no duplication)	0.40 km	0.2	1.5	8.4	79.5	45,626	12,268	4
9	Improve Delineation	8.70 km	2.32	15.4	83.8	795.1	456,258	125,920	4

It seems possible that these results are due to a higher unit cost for crashes compared to that for casualties. In addition, the number of crashes although lower in all severity levels does not significantly differ from that of casualties.

The other possible explanation for the increase in monetary savings is due to the addition of safety benefits resulting from PDO crashes. Although PDO crashes constitute over 80% of the total crashes (Park *et al.,* 2012), they are not included in the casualty-based approach. An implication for this is that the casualty–based approach may lead to underestimation of economic benefits. For instance, in the crash/casualty data analysed by this research for 9 countries, the PDO crashes were 90% of the total crashes. Further analysis showed that the PDO crashes account for 30% of the total cost of crashes. This is comparable to the average of 39% established for LMICs by Wijnen and Stipdonk (2016) as the share of PDO crashes in the total cost of crashes. Therefore, the inclusion of PDO crashes in economic analysis is substantial as previously argued by Wijnen *et al*. (2017) and their exclusion can significantly result in underestimation of total costs (Wijnen *et al.,* 2019).

6.4 Discussion

6.4.1 Comparing the total cost of crashes and casualties

The results show that the total cost of crashes is generally higher than that of casualties in all countries. In countries like Finland and Norway, the total cost of crashes is much higher since 99% of the total crashes are PDO crashes. On average, the PDO crashes are approximately 90% of the total number of crashes and these account for over 30% of the total cost of crashes which agrees with the previous findings by Wijnen *et al.* (2017) where in Germany and Finland the PDO crashes had a share of up to 50% of the total cost of road crashes. Similarly, in a study conducted in Singapore, the PDO crashes were 50% of the total cost of crashes (Chin, 2003). In addition, in the Netherlands, about 24% of the total cost of crashes is attributable to PDO crashes (SWOV, 2020). This seems to indicate that PDO crashes generally have a significant impact on the total cost of crashes and thus on the results of an economic analysis of countermeasures.

Therefore, in an economic appraisal of road safety countermeasures, considering the number of crashes prevented may give a more realistic representation of the actual benefits that might accrue with countermeasure implementation than the casualty approach. In addition, the safety benefits are higher in a crash-based approach as the crash unit cost is usually higher than a casualty unit cost since crashes include one or more vehicles and persons (Wijnen *et al.,* 2017; De Brabander and Vereeck, 2007).

6.4.2 The impact of economic analysis approaches on countermeasure selection (All case studies)

Firstly, this section compares the unit costs used in these case studies in the application of the different economic analysis approaches. Secondly, the results from these case studies due to the application of the different economic analysis approaches are equally discussed.

1. Crash/casualty unit costs

Unit costs used in both case studies are clearly distinguished as crash and casualty unit costs. These unit costs vary for the different severity levels. The unit cost of crashes is higher than the casualty unit costs in both case studies. However, the unit costs in the Indonesia case study are much higher (50%) compared to those in the Netherlands case study (20%). The accuracy of these unit costs in both case studies may be used to explain this difference. Crash and casualty unit costs were applied to the number of crashes and casualties respectively in both case studies.

Generally, unit costs used in the Netherlands case study are incomparable to those in the Indonesia case study despite similar cost components. The unit costs used in the Indonesia case study are on average 2% of the unit costs used in the Netherlands case study. This may be explained largely by the difference in economic power between the two countries. However, in both case studies, the unit cost of preventing a slight injury is 1% of the value of a fatality, which falls in the range of 0.03%–4.4% earlier established by Wijnen *et al.* (2019). Further analysis shows that the unit cost of a slight injury is 1.2% of the total cost of all severity levels in the Indonesia case study compared to 1.05% in the Netherlands cases study. The unit cost of preventing a PDO crash is 1% of the total cost of preventing all severity levels in the Indonesia case study compared to 0.1% in the Netherlands case study. The differences in unit costs may affect the computation of economic safety benefits and subsequently the selection of countermeasures.

The unit costs used in the Netherlands case study consist of both injury and crash related costs (Wijnen *et al.,* 2017) and the Indonesia unit costs consist of both direct and indirect costs (Sugiyanto and Santi, 2017). These cost components are similar and generally consist of property damage, loss of productivity, medical, administrative, costs incurred by the relative/family of the accident victim, costs of pain, grief and suffering.

2. Application of economic analysis approaches

The results from both case studies demonstrate that iRAP's economic analysis approach may underestimate the computation of economic safety benefits. There are several possible explanations for these results. The first possible explanation is the fact that the iRAP approach considers only two casualty severity levels (fatalities and serious injuries) and doesn’t take into consideration the economic benefits that may be achieved due to a reduction in slight injuries. The second possible explanation for these results is that iRAP is a casualty-based model, which considers the number of casualties saved instead of crashes as the safety benefits due to countermeasure implementation.

The present study raises the possibility that the iRAP approach appears to limit the number of countermeasures that may be economically justified. The increase in economic safety benefits and the number of countermeasures selected in the casualty-based approach compared to the iRAP approach supports this argument. Slight injuries that are not included in the iRAP approach constitute over 85% of the total number of casualties (Morris *et al.,* 2006) and this may result up to 20% underestimation of economic safety benefits (Byaruhanga and Evdorides, 2021). Therefore, the iRAP approach appears to exclude a significant number of casualties prevented due to the implementation of countermeasures that equally prevent slight injuries. The number of slight injuries saved coupled with a substantial unit cost contribute significantly to the computation of economic safety benefits.

In the Netherlands case study, the economic benefits increased by 28% with a change from the iRAP approach to the casualty approach, which is slightly lower than 45% obtained in the Indonesia case study. A possible explanation for these differing percentages is the difference in the unit costs of a slight injury identified in crash/casualty unit costs section above.

Similarly, both case studies demonstrate that a crash-based approach is superior to a casualty-based approach due to improved accuracy in the computation of economic benefits that results in selection of more countermeasures for implementation. There are several possible explanations for these findings, but key among them is the case for PDO crashes. Largely, PDO crashes included in the crash-based approach are usually over 80% of the total number of crashes as established by this research and previously by Park *et al.* (2012). It appears that a casualty-based approach excludes a significant number of crashes not involving casualties. However, the increase in economic benefits in the Indonesia case study of 156% is sixfold that of the Netherlands case study due to the differences in the unit cost of PDO crashes as a percentage of the total cost of all severity levels identified in the crash/casualty unit costs section above. There is more economic weight in saving a PDO crash in Indonesia than in the Netherlands. Generally, since the casualty-based approach doesn't include PDO crashes, it may be inferred that a casualty-based approach may underestimate economics safety benefits up to 30%.

To sum it up, the similarities of the findings from these case studies demonstrate the possibility of improved accuracy in computing economic benefits using the number of crashes and their respective unit costs instead of casualties.

6.5 Summary

This Chapter has presented an analysis conducted between crash-based and casualty-based economic approaches of infrastructure countermeasures to inform economists and road safety analysts on the most appropriate approach. This research utilised data from 9 countries and the 20-year infrastructure improvement programmes for Netherlands and Indonesia as case studies.

The first important finding by this study is that the cost of crashes is higher than that of casualties. The comparative study results demonstrated that a crash-based approach is more comprehensive and results in a wider range of countermeasures selected for implementation. In addition, compared to a casualty-based approach the value of safety benefits and the number of countermeasures selected increased using a crash-based approach. Therefore, any road safety appraisal model may perform better by considering crashes instead of casualties and more so if the PDO crashes are included in the analysis. Consequently, the next Chapter of the conceptual design of the model uses the number of crashes and crash unit costs to compute economic safety benefits of infrastructure countermeasures.

CHAPTER 7: CONCEPTUAL DESIGN OF THE MODEL

7.1 Introduction

Road safety budgets are under financial constraints which means that not all the worthy countermeasures will be implemented (PIARC, 2021). The use of economic efficiency tools like CBA and CEA alone cannot provide optimal results. This calls for an optimisation technique for optimal allocation of limited resources to maximise the safety benefits across the road network.

This Chapter describes such a methodology that prioritises countermeasures and allocates the available budget in a road safety programme constrained financially. A conceptual framework representing this process and the relationships between its variables is also given.

7.2 Conceptual model

According to Robinson (2008), a conceptual model is a non-software specific description/illustration of the model to be developed, consisting of objectives, inputs, outputs, content and identifying any assumptions and simplifications. A conceptual model minimises the likelihood of incomplete, unclear and inconsistent requirements while guiding the development, which thus forms the basis for verification and validation of the actual model (Robinson *et al.,* 2015). Figure 7.1 presents a theoretical framework showing the key components of this conceptual model.

7.2.1 A programme of countermeasures

An ideal infrastructure countermeasure programme normally consists of a list of cost-effective measures or treatments aimed at making safety improvements on the road network. It can either be project or network level-based consisting of reactive (applied to existing infrastructure) or proactive (applied to new roadways/major improvement to an existing roadway) measures (Sayed *et al.,* 2010) developed through a systematic procedure as part of a road safety improvement programme. These countermeasures may be implemented on a particular roadway section and over the entire road network thus the terminology project and network level respectively (Horton, 1990).

However, this research aimed at determining the best budget allocation strategy for capital and maintenance countermeasures implemented over the entire road network, thus network level programme of countermeasures. Such a programme of countermeasures is a key input of this model to be developed. The model requires this list of countermeasures consisting of costs and economic benefits of each countermeasure. iRAP's methodology develops this programme of countermeasures usually termed as SRIP consisting of the implementation costs and the number of casualties saved over the analysis period. The following sections describe the key steps in developing a road infrastructure programme of countermeasures based on the iRAP methodology.

1. **Screening of the road network**

This is the first step in developing a programme of infrastructure measures to improve the road safety condition of the network. In this step, a road network is reviewed or assessed to identify risks, deficiencies or crash patterns and their contributing factors. There are two approaches employed in screening the road network. A crash-based approach involves screening specific road network sites to select and treat them based on site-specific crashes. The other more systematic approach, such as that employed by iRAP, involves assessing the road network with regard to existing high-risk roadway attributes or features. iRAP's methodology divides the road network into 100m road segments assessed in terms of specific geometry and operational road attributes and their deficiencies.

2. Identification of countermeasures

The output of the above process results in a list of countermeasures proposed and recommended to improve the safety condition of each road segment subject to a set of triggers (or prerequisite conditions). A countermeasure may be identified and considered subject to satisfaction of one or more of, the star rating, road attribute and vehicle flow. For instance, a poor delineation observed during road network screening leads to the identification of the 'improve delineation countermeasure' (iRAP, 2015b).

3. Countermeasure effectiveness

Risk factors or CMFs applied in the iRAP approach are used to determine countermeasure effectiveness. These CMFs determine the crash reduction potential of a countermeasure at a given location, which then determines its effectiveness. The approach involves applying CMFs to an estimated number of fatalities and serious injuries that occur on each 100m segment of the existing road under existing conditions. The number of fatalities on every 100m road segment is calculated as the sum of the fatalities for the road users (vehicle occupant, motorcyclists, pedestrians and bicyclists) which is a function of star rating score (representing the risk of death and serious injury), vehicle, pedestrian or cyclist flow. The number of serious injuries is a ratio of fatalities (ten serious injuries for each fatality).

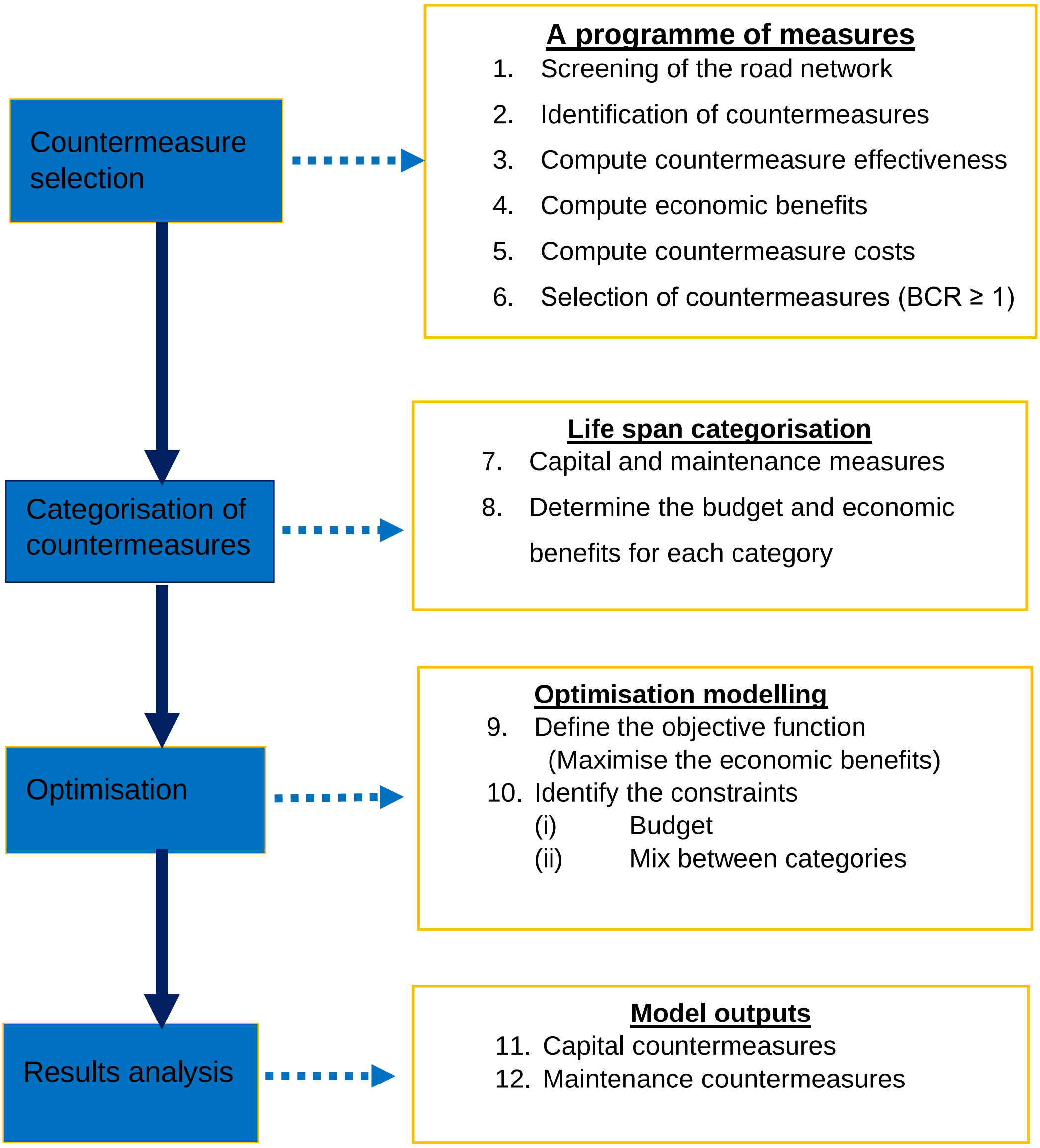


Figure 7.1 Theoretical framework

4. Economic benefits of countermeasures

The quantitative and qualitative impacts of safety investments are important in an economic appraisal to improve the consistency and reliability of decisions when evaluating and ranking countermeasures (Lawrence *et al.,* 2018). It is important to consider all relevant effects on safety, travel time, environment and operational conditions due to their substantial influence on the results of a CBA (Martensen and Lassarre, 2017). However, in some of the most widely used road safety investment appraisal tools such as SafetyAnalyst (AASHTO, 2020) and iRAP (2015); safety benefits relating to reduced number of crashes or casualties are only considered ignoring the indirect benefits that relate to mobility (travel time and vehicle expenses) and environment (noise and pollution).

However, the E^3 tool considers these indirect benefits of safety measures if known by analysts although the economic evaluation of other possible impacts was out of the scope for the SafetyCube project (Martensen *et al.,* 2018). Similarly, some CBA studies conducted for safety measures consider benefits as reduced number of crashes or injuries (Daniels *et al.,* 2019) and appear to ignore the side effects due to lack of models to evaluate them (Yannis *et al.,* 2008).

This Thesis uses the number of crashes together with the crash unit rates to determine the economic benefits instead of using casualty numbers. Crash numbers used in this study were determined based on the number of fatalities and serious injuries determined by iRAP methodology.

5. Life cycle costs of countermeasures

The computation of life cycle costs of countermeasures is one of the key parameters required to conduct economic analysis. According to Herbel, Laing and McGovern (2010), all the costs incurred over the service life of the project including future maintenance or operation costs should be included in present value cost computation for safety measures. Consequently, the implementation costs of infrastructure safety countermeasures are the investment costs and the annual costs of maintenance and operation.

The concept of life cycle is useful in understanding and determining the overall measure costs over the entire analysis period, which is key to efficient allocation of resources (Furuta *et al.,* 2003). Generally, economic life cycle costs incurred directly by road agencies from planning to disposal recommended by Lawrence *et al.* (2018) are required to compute life cycle costs of measures.

However, according to Byaruhanga and Evdorides (2022), there are no standardised methods for combining life cycle costs of road safety countermeasures during appraisal and all methods ignore infrastructure end of life costs. Costs related to disposal or removal, recycling and sale of safety measures constitute the end of project costs usually referred to as salvage values (FHWA, 2002; Lawrence *et al.,* 2018). Salvage value represents the value of the countermeasure at the end of its defined service life minus the costs involved in removal, demolition or sale of any components (Bowman, 1986). As an example, a traffic signal removed at the end of its defined service life will either have a value as a signpost or scrap material. Relatedly, the other value considered at the end of the appraisal period is the remaining service life (RSL) or residual value (FHWA, 2002). The RSL values apply to continued operation or use of the countermeasure when the service life extends beyond the analysis period.

The notion that end of life infrastructure costs represent a small difference in economic analysis may not be applicable in case of multiple treatments with unequal service lives when included in network level analysis. For instance, some studies have shown that costs to remove safety barriers are about 20% of construction costs (Kristowski *et al.,* 2018). DfT (2018) recommends including salvage or residual values in CBA of projects with finite lives of fewer than 60 years. The importance of including maintenance and repair or replacement costs for countermeasures such as roadside safety barriers cannot be overemphasized because these costs may exceed construction costs significantly due to increased crash frequency (Jamroz *et al.,* 2018). Similarly, according to Wanyama *et al.* (2003), several life cycle studies conducted appear to agree that maintenance costs dominate life cycle costs. In practice, life cycle costs of safety measures are seldom during economic appraisal, which leads to unrealistic road safety investment decisions.

Nonetheless, this study adopted iRAP's costs of countermeasures used to develop the infrastructure programme. These costs are determined considering construction costs categorised by area type (urban and rural) and cost type (low, medium and high) as well as the service life for each of the countermeasures. If for instance, a countermeasure has a service life of 10 years, considering an analysis period of 20 years, then its costs would be construction costs at the start and then reconstruction costs 10 years later.

6. Selection of countermeasures

This step involves selecting countermeasures from the list of recommended measures identified during the screening the road network. The criterion for selection includes an economic test, minimum length and minimum spacing and hierarchy rules (iRAP, 2015b). For instance, for each countermeasure selected, its BCR must exceed a prescribed threshold set by the analysis team. The above criteria applies to all countermeasures selected for each of the 100m road segments. Therefore, for countermeasures not triggered during this selection process are those that cannot satisfy the rules.

7.2.2 Life span categorisation

The road network composed of sections and junctions, built to engineering standards will usually require improvements and modifications due to changes mainly in traffic volumes and safety condition thus the need for different categories of measures. According to Elvik (2014), obtaining the best mix of short-term and long-term measures in a road safety programme is still one of the problems in determining the optimal use of road safety countermeasures. In addition, the fact that measures with different life spans are not directly comparable has not received due attention.

Previous optimisation models (Melachrinoudis and Kozanidis, 2002; Mishra, 2013; Mishra and Khasnabis, 2012; Saha and Ksaibati, 2016) allocated budgets amongst measures, highways, intersections or black spots but none of these considers the life span of countermeasures. In the scholarly literature (Elvik, 2014; Uden and Heijkamp, 1995; Weber and Jahring, 2010), the terms short-term, medium-term and long-term categorise measures though with no clear distinction. Different perspectives of lives for road safety countermeasures exist in the literature; physical, economic and design lives. In most cases, the lives used are not clearly distinguished as to whether economic or design lives except in Elvik *et al*. (2009) where this refers to both technical (i.e., life to failure) and economic lifetime of the measures. Similarly, De Pauw *et al*. (2018) uses the term economic lifetime of the measure in determining the safety effects of dynamic speed limits on motorways. It appears that during economic appraisal of infrastructure countermeasures, different lives are applied and possibly these terms are used interchangeably.

Road safety countermeasures may be implemented as part of a capital or a maintenance works programme (Mahmud, Ahmed and Hoque, 2014; Tziotis, 2011). Consequently, this research tentatively suggests, and subsequently considers, that countermeasures with a life span more and less than 10 years may be termed as capital and maintenance respectively. The model requires that the individual countermeasures in an infrastructure improvement programme described in the previous section should be categorised as either capital or maintenance countermeasures. This is a key requirement of the model and a novel aspect introduced in the prioritisation process. Arguably, the above categories of countermeasures are not comparable and thus any prioritisation process that does not distinguish them may produce biased results. Categorisation facilitates the integration of countermeasures required to enhance sustainability of assumed economic benefits. Consequently, the budget and economic safety benefits for each category are then determined.

7.2.3 Optimisation modelling

The key components of this stage are the objective function and constraints of the model presented below.

1. **Objective of the model**

As identified in the previous Chapter, a crash-based approach is adopted by this research as it may improve the accuracy of computing economic safety benefits of road safety infrastructure countermeasures. Thus, in defining the objective function of the model, the number of crashes together with the crash unit rates are considered in determining the economic safety benefits. Consequently, the objective of this model is to maximise the overall economic benefits due to integration of countermeasures more especially in a financial constraint. In addition, the proposed model determines the prioritisation of countermeasures in each category required to enhance sustainability of economic benefits.

2. **Model constraints**

Constraints are included in the modelling process to express restrictions that are important in achieving the main objective. In this conceptual model, the constraining the prioritisation and allocation of the available budget to the different categories of countermeasures is very important. The following are the key constraints to the model.

i. The total cost spent on capital and maintenance countermeasures must be less or equal to the available budget.
ii. The prioritisation process must ensure a mix between capital and maintenance countermeasures.

7.2.4 Model outputs

The outputs of the model are as follows.

i. The prioritised list indicating the number of countermeasures in each category selected for implementation in each budget scenario.
ii. The monetised economic benefits in each budget scenario due to the selection of countermeasures above.
iii. The split of the available budget to capital and maintenance countermeasures, which is the total cost of countermeasures in each category.

7.3 Summary

This Chapter presents a conceptual model that provides a systematic procedure to optimise a road safety budget. It gives its objectives, inputs, and outputs, content and underlying constraints considered by this research.

The model’s objective is to maximise the overall economic benefits due to countermeasure implementation obtained through a mix of both capital and maintenance countermeasures. The required model inputs are an infrastructure countermeasure programme that consists of a list of cost-effective countermeasures. The key parameters required by the model are the life cycle costs and economic benefits of the countermeasures. The main constraint of the model is that the total cost of implementing countermeasures should be equal or less than the available budget. Finally, countermeasures prioritised, and the amounts of resources allocated to each category are the expected model outputs.

All the above concepts are taken into consideration in the next Chapter of model development.

CHAPTER 8: MODEL DEVELOPMENT

8.1 Introduction

This research formulated an optimisation model as a MILP problem that can use both continuous and integer decision variables. The optimisation problem seeks to find the optimal balance between capital and maintenance measures in a safety programme considering budget constraints. Identifying the need for optimisation, choosing the design or decision variables, formulating the objective function and specifying constraints to the model are the key steps of model development (Alrabghi and Tiwari, 2016) presented in this Chapter.

The key parameters required to develop and run the model are the countermeasures grouped into two categories with regard to their life span together with their individual life cycle costs and economic safety benefits. This Thesis introduces a unique concept of grouping countermeasures with regard to their life span as part of the prioritisation procedure. The model proposes two main categories of safety infrastructure countermeasures (capital and maintenance).

Life cycle costs are the costs incurred during the appraisal period consisting of construction, operation, and maintenance and possibly end of infrastructure life costs (Lawrence *et al*., 2018). In computing the economic benefits, investment appraisal models consider the reductions in the number of crashes or casualties as the safety benefits due to implementation of countermeasures (Byaruhanga and Evdorides, 2021). However, according to Byaruhanga and Evdorides (2022), any investment appraisal model may perform better by considering the number of crashes instead of casualties and more so if PDO crashes are included in the analysis. For this reason, this study uses the number of crashes together with the crash unit rates to determine the economic benefits instead of using casualty numbers.

In model development, the main objective is to describe the optimisation problem by defining the objects and the data required, decision variables, objective function and constraints.

8.1.1 Value of the model

The developed model gives guidance on the best approach to compute economic safety benefits while providing flexibility to analysts with limited data on crash severity levels. The model advocates the application of a crash-based approach to compute economic safety benefits. A crash-based approach contributes to realistic computation of benefits that enhance business proposals presented for road safety infrastructure investments. Arguably, unrealistic computation of safety benefits may result in under investments in road safety.

It is also possible that data on some crash severity levels, or crash unit rates is not available in some countries, which may lead to computation of economic safety benefits without all the crash severity levels. As an example, data on PDO crashes and their unit rates may be limited in LMICs. Therefore, this model offers flexibility to apply infrastructure countermeasure programmes where economic benefits are computed with 2 or 3 crash severity levels.

World over, financial constraints are inevitable and so determining countermeasures with the highest priority is very crucial. Under such circumstances, balancing the budgetary needs for different categories of countermeasures becomes more challenging. For instance, there is a tendency of prioritising maintenance over capital measures due to their cost effectiveness. The novelty of the model resides in integrating these two categories of countermeasures thus providing a practical solution to this challenge.

Furthermore, the provides practical demonstration of the value of this distinction between capital and maintenance countermeasures in both developed and developing countries. Ultimately, the main goal of this model was to determine the optimal expenditure between capital and maintenance countermeasures to maximise the economic benefits under a constrained budget. This optimal expenditure comes from the selection and prioritisation of countermeasures in each budget scenario that provides the greatest economic return.

Again, considering financial constraints, the use of an economic selection criteria such as BCR until the available resources are exhausted appears ineffective. Therefore, the application of this model guarantees effectiveness and full utilisation of available resources provided through a balanced selection of the different categories of countermeasures.

8.2 Mixed integer linear programming

In road safety, dynamic programming (Brown, 1980), linear programming (Behnood and Pino, 2020; Saha and Ksaibati, 2016; Kar and Datta, 2004) and integer programming (Abdolmanafi and Karamad, 2019; Melachrinoudis and Kozanidis, 2002; Mishra and Khasnabis, 2012) techniques have been applied. Dynamic programming is a technique that solves a complex problem through a sequence of simpler sub problems (Howard, 1966; Rust, 2008). Linear programming technique expresses resource allocation problems mathematically in form of linear equations and inequalities (Murota, 2020; Williams, 2009). Integer programming is an optimisation technique in which all the variables are restricted to integers (Milano and Trick, 2004). It appears there is recent application of linear, integer programming or both and more specifically the use of the faster and advanced branch–and–bound technique (Przybylski and Gandibleux, 2017).

Melachrinoudis and Kozanidis (2002) developed a mixed integer allocation model for discrete (at specific points on the road network) and continuous (over the length of the road) improvements to maximise the reduction in the expected number of accidents. Kar and Datta (2004) used a linear programming technique in allocating resources in the state of Michigan to maximise the benefits of reducing total crashes. Similarly, Behnood and Pino (2020) developed a model to minimise a cost effectiveness index (CEI) excluding PDO crashes. An optimisation model by Mishra and Khasnabis (2012) allocated resources to maximise monetary benefits due to saved crashes at urban intersections. Another model developed for the best mix of countermeasures to improve black spots by Saha and Ksaibati (2016) allocated resources by maximising benefits in terms of reduced overall crash frequency but ignored PDO crashes.

This Thesis formulated a budget allocation problem using MILP. MILP often used for system analysis, optimisation problems and with a wide application in efficient use of limited resources offers a very flexible and powerful method for solving large, complex problems (Kantor, 2020). There is success in the use of MILP due to its flexibility and the availability of MILP based commercial and non-commercial solvers (Vielma, 2015). MILP is a mathematical programming technique in which the objective function and all the constraints are linear with variables constrained to be integers and others non-integers (Urbanucci, 2018). This technique involves the use of continuous variables that can take any real value and binary decision variables that can take a value of 1 or 0. The key feature of MILP is the use of these binary decision variables which are considered important in resource allocation problems where discrete decisions are required. Modelling mixed integer problems is typically a three-step process that includes defining decision variables, statement of the objective function and finally a statement of a set of constraints. Equality and inequality constraints are the limitations of the actions or decisions in the system. These are elaborated as follows.

8.3 Decision variables

The formulation of an optimisation model begins with decision variables that may change in the optimisation process. These are the most important parameters that determine the value of the objective function. The economic safety benefits computed using the number of crashes saved and their respective crash unit costs constitute the decision variables (Table 8-1). Discounting applied while conducting economic appraisal enables monetary values at different times of the analysis period comparable (Martensen *et al.,* 2018) Therefore, the above are the discounted monetary benefits of countermeasures over a given analysis period.

Table 8-1 Decision variables

Decision variables	**Description**
f_i^c	The number of fatal crashes reduced by a capital countermeasure (i)
f_k^m	The number of fatal crashes reduced by a maintenance countermeasure (k)
s_i^c	The number of serious injury crashes reduced by a capital countermeasure (i)
s_k^m	The number of serious injury crashes reduced by a maintenance countermeasure (k)
sl_i^c	The number of slight injury crashes reduced by a capital countermeasure (i)
sl_k^m	The number of slight injury crashes reduced by a maintenance countermeasure (k)
Pdo_i^c	The number of PDO crashes reduced by a capital countermeasure (i)
Pdo_k^m	The number of PDO crashes reduced by a maintenance countermeasure (k)
f_c	A unit cost for a fatal crash
s_c	A unit cost for a serious injury crash
sl_c	A unit cost for a slight injury crash
pdo_c	A unit cost for a PDO crash
X_i	This takes the value of 1 after selecting a capital countermeasure as part of the solution and 0 otherwise
X_k	This takes the value of 1 after selecting a maintenance countermeasure as part of the solution and 0 otherwise

8.4 Objective function

The subsequent stage in model development involved the formulation of the objective function in terms of decision variables. The objective function, expressed in a mathematical form during modelling, defines the objective that can either be a minimisation or maximisation type. The objective in this study is to find the best combination of countermeasures that maximises the economic safety benefits for a given funding. The best combination is achieved through categorisation of countermeasures as either capital or maintenance as part of the prioritisation process. The selection of countermeasures in each category ensures the most efficient use of the available resources for a road safety programme. To achieve the above, the model takes into account the costs of implementation and the associated economic benefits for each countermeasure as the basis for budget allocation. Therefore, the objective function (Z) in Equation 8.1 maximises the economic safety benefits due to reductions in fatal, serious, slight and PDO crashes. As previously discussed, a crash-based approach that is superior to a casualty-based approach is used to compute economic benefits. These are the monetised benefits computed at the end of the appraisal period taking into consideration discounting. The objective function further ensures integration of countermeasures so as to achieve sustainability of economic benefits.

$$Z = Max \sum_{i=1}^{N} \sum_{k=1}^{K} \begin{bmatrix} (f_i^c f_c + s_i^c s_c + sl_i^c sl_c + Pdo_i^c pdo_c) X_i + \\ (f_k^m f_c + s_k^m s_c + sl_k^m sl_c + Pdo_k^m pdo_c) X_k \end{bmatrix} \tag{8.1}$$

$N \; and \; K$ represent the total number of capital and maintenance measures respectively. $X_i \; and \; X_k$ are binary decision variables (1 if selected, otherwise 0). As previously defined, the terms used in the objective function represent the parameters used to compute economic safety benefits.

8.5 Constraints

Constraints form the final component of model development and ensure the desired and realistic model output. In the attainment of the objective function, the model constraints must be satisfied. The growing competition for limited resources implies that road safety budgets will always be insufficient due to cuts and diversions to handle other priorities. This is a typical challenge for organisations or agencies involved in road network safety improvement programmes. As a result, the model is constrained by the availability of funds to implement a set of countermeasures in a road infrastructure improvement programme. The actual total life cycle costs for capital and maintenance countermeasures should not exceed the available funds. Therefore, the main limitation of the model is a total budget (B) that determines the optimal expenditure between the two categories of countermeasures given by equation 8.2.

$$\sum_{i=1}^{N}\sum_{k=1}^{K}[(C_i^c)X_i + (C_k^m)X_k] \leq B \tag{8.2}$$

$$N_B^c = N_B^m \tag{8.3}$$

$$X_i \in \{0,1\} \tag{8.4}$$

$$X_k \in \{0,1\} \tag{8.5}$$

The second constraint (Equation 8.3) ensures optimal mix between countermeasures from the two categories. $N_B^c \; and \; N_B^m$ are the number of selections made for capital and maintenance countermeasures respectively with the available budget (B). C_i^c and C_k^m are the discounted costs of implementation for capital countermeasure i and maintenance countermeasure k respectively. N and K represent the total number of capital and maintenance countermeasures respectively. X_i and X_k (Equations 8.4 and 8.5) are the binary decision variables (1 if selected, otherwise 0).

8.6 Summary

An optimisation model that seeks to find the optimum balance between capital and maintenance measures in a safety programme considering budget constraints is developed. MILP often used for system analysis, optimisation problems and with a wide application in efficient use of limited resources is the basis in developing this model. Identifying the need for optimisation, choosing the design or decision variables, formulating the objective function and specifying the constraints are the main steps followed to develop the model.

The number of crashes saved, and the crash unit rates at different crash severity levels for each countermeasure constitute the decision variables. Thus, the objective function maximises the economic safety benefits due to reductions in fatal, serious, slight and PDO crashes. The developed model is constrained by the availability of funds to implement a set of countermeasures in a road network safety investment programme. In addition, the model is constrained to ensure a mixed selection between capital and maintenance countermeasures.

The illustration of the practical application of this newly developed model is presented in the next Chapter of model application.

CHAPTER 9: MODEL APPLICATION

9.1 Introduction

To illustrate the application of the proposed model, the two case studies considered throughout this Thesis were used with the view to provide the mathematically optimum expenditure for each category of countermeasures for a given budget. This study considered budget limitations and the LINGO software (LINDO, 2020) to run the developed model. The study assumes 3 budget scenarios representing the limitation of road safety budgets in practice. Finally, the study further appraises the newly developed approach by comparing it with a non-life span optimisation approach.

9.2 Computational procedure

In order to implement the proposed approach, a list of countermeasures in a road network safety investment programme consisting of implementation costs and the resulting economic benefits are required as input data. Consequently, this research adopted iRAP's procedure for developing such a list of infrastructure countermeasures and only modified the economic appraisal element particularly the computation of economic safety benefits.

As a result, road safety investment plans that were developed using iRAP's procedure were used as case studies/input data. The costs and benefits presented in these case studies are net present values estimated using a real discount rate. A real discount rate may be obtained by removing the rate of inflation as measured by the consumer price index (CPI). The procedure adopted by this research converting casualties (fatalities and serious injuries) into crashes (fatal, serious, slight and PDO) and all the other necessary modifications to the original data are presented in Chapter 6. Consequently, the economic safety benefits used in these case studies were computed by multiplying the number of crashes saved in each crash severity level with the respective crash unit rates. Furthermore, the proposed approach requires categorising measures using their life spans (life-span optimisation approach). Consequently, the life years (service or treatment life) of countermeasures obtained from different sources was used to categorise each countermeasure as either capital or maintenance. In the non-life span optimisation approach, the countermeasures were not categorised during optimisation process. The total costs and economic benefits for capital and maintenance countermeasures in the unconstrained budget scenario (100% budget availability) were obtained as a sum in each category.

Validation was conducted before applying the model to the case studies. Model validation is an important process during development by evaluating whether the model performs as expected and achieves its intended purpose. In this study, the model was tested to ascertain the extent to which it would allocate the available resources subject to a set of constraints. Using a real data set, the model was validated by checking the optimal solution provided by the solver to ascertain whether it was logical and sound. The solution from application of the model was tested to ensure all the constraints were not violated. Furthermore, some of the elements of input data were varied to observe the changes on the solution provided by the solver. As an example, different values of the available budget (budget scenarios) were used to observe the changes in the outputs by the model. Generally, the trial results from the application of the model indicated a satisfactory performance that further led to the application of the model to the two case studies (Netherland and Indonesia).

The output from the application of the model to these case studies was further summarised to obtain the total number of countermeasures selected, costs and economic benefits for capital and maintenance categories in all the budget scenarios. In addition, the percentages for the total budget allocated and the economic benefits achieved in each category of the countermeasures was computed. The above computations were then summarised for each case study and for all budget scenarios. Furthermore, the total number of crashes reduced for the different budget scenarios in all case studies was computed. The iRAP's safety investment plans developed for the Netherlands and Indonesia that were further modified by this research and used as case studies/input data are presented in the sections below.

9.3 The Netherlands case study

The provincial roads that contribute 6% of the total Dutch network were among the most unsafe roads with a risk of a serious accident five times higher in comparison to the national road network (ANWB, 2013). Consequently, in 2012 and 2013, the Royal Dutch Touring Club (ANWB) assessed these roads using EuroRAP methodology to recommend effective road safety improvements to prevent these accidents. The results of assessment showed that over 65% of Utrecht provincial road network (332 km) had a rating of 2 stars (unsafe condition).

This case study consists of realistic and effective countermeasures based on these results to improve the assessed road network to a minimum safety level of 3 stars (safe condition). Unlike SafetyAnalyst model, iRAP is a casualty-based model that considers only 2 severity levels (fatalities and serious injuries) that may underestimate economic safety benefits (Byaruhanga and Evdorides, 2022). As a result, a more effective approach that uses crash numbers instead of casualty numbers and considering 4 severity levels (fatal, serious injury, slight injury and PDO) is preferred.

9.3.1 Input data

An ideal road network safety infrastructure programme consists of the data required to apply the newly developed optimisation model. In this research, part of the Utrecht infrastructure programme shown in Table 9-2 modified by Byaruhanga and Evdorides (2022) was used as input data to demonstrate the practical application of this model. Regarding categorisation, measures with life years more and less than 10 years are categorised as capital (C) and maintenance (M) measures respectively (Table 9-1). The measures in this case study categorised based on this criterion are similar to those included in a capital and maintenance works programmes by Tziotis (2011).

Table 9-1 Life years of countermeasures (Netherlands)

Countermeasure	Life years	Category	Source of information
Pedestrian footpath	10 – 20	Capital	iRAP, 2010
Median barrier	10 – 30	Capital	PIARC, 2021; iRAP, 2010; Grzyl *et al.,* 2017
Roadside barrier	10 – 30	Capital	iRAP, 2010; Daniels and Papadimitriou, 2017; Daniels *et al.* , 2019; Grzyl *et al.,* 2017
Pedestrian fencing	10 – 20	Capital	iRAP, 2010
Street lighting	10 – 20	Capital	iRAP, 2010
Traffic calming	10 – 20	Capital	iRAP, 2010
Bicycle lanes and tracks	10 – 25	Capital	Elvik *et al.,* 2009; iRAP, 2010
Reconstruction and rehabilitation of roads	25	Capital	Elvik *et al.,* 2009
Pedestrian crossing (signalised)	10 – 20	Capital	iRAP, 2010
Sight distance (obstruction removal)	5 – 10	Maintenance	iRAP, 2010
Shoulder rumble strips	1 – 5	Maintenance	iRAP, 2010
Refuge island	5 – 10	Maintenance	iRAP, 2010
Protected turn lane (unsignalised 4 leg)	5 – 10	Maintenance	iRAP, 2010
Unsignalised crossing	1 – 5	Maintenance	iRAP, 2010
Central hatching	1 – 5	Maintenance	iRAP, 2010
Parking improvements	5 – 10	Maintenance	iRAP, 2010
Centreline rumble strip / flexi-post	1 – 5	Maintenance	iRAP, 2010
Improve delineation	1 – 5	Maintenance	iRAP, 2010
Protected turn lane (unsignalised 3 leg)	5 – 10	Maintenance	iRAP, 2010
Wide centreline	5 – 10	Maintenance	iRAP, 2010
Delineation and signing (intersection)	1 – 5	Maintenance	iRAP, 2010
Clear roadside hazards - driver side	5 – 10	Maintenance	iRAP, 2010
Shoulder sealing passenger side (>1m)	5 – 10	Maintenance	iRAP, 2010

Road authorities and other agencies take into consideration the available resources and other limiting conditions such as the desired BCR in the implementation of such capital-intensive safety programmes. Further analysis of the original data in this case showed that a total of € 71 million was required to implement countermeasures to yield economic safety benefits of € 590 million (Table 9-2). In view of the growing funding limitations of safety budgets, it is possible that 80%, 60%, or even 25% of the budget is available for this programme (Table 9-3). Based on this data, the developed model was used to optimise the available funds to improve the safety condition of the road network by maximising the economic safety benefits.

Table 9-2 A programme of countermeasures (Netherlands)

S/N	Countermeasure	Category	Length / sites	Crashes minimised				Economic benefits (€)	Costs(€)	BCR
				Fatal	Serious injury	Slight injury	PDO			
1	Signalised crossing	C	1 sites	1.2	7.7	41.9	397.5	8,829,598	45,000	196
2	Pedestrian fencing	C	27.20 km	1.0	6.9	37.7	357.8	7,946,638	179,606	44
3	Street lighting (intersection)	C	14 sites	2.4	16.1	88.0	834.8	18,542,156	504,000	37
4	Traffic calming	C	2.90 km	0.1	0.8	4.2	39.8	882,960	87,581	10
5	Central median barrier (no duplication)	C	0.70 km	0.1	0.8	4.2	39.8	882,960	95,182	9
6	Footpath provision driver side (>3m from road)	C	25.40 km	3.3	21.5	117.4	1113.1	24,722,875	2,922,040	8
7	Footpath provision passenger side (>3m from road)	C	26.80 km	3.4	22.3	121.6	1152.9	25,605,835	3,085,368	8
8	Footpath provision driver side (informal path >1m)	C	4.70 km	0.1	0.8	4.2	39.8	882,960	114,747	8
9	Footpath provision driver side (adjacent to road)	C	27.90 km	4.1	26.9	146.7	1391.4	30,903,593	4,388,280	7
10	Bicycle Lane (off-road)	C	3.50 km	0.3	2.3	12.6	119.3	2,648,879	392,156	7
11	Footpath provision passenger side (adjacent to road)	C	44.10 km	6.0	39.9	218.0	2067.2	45,913,910	6,939,120	7
12	Roadside barriers - driver side	C	206.20 km	23.1	152.9	834.1	7911.1	175,709,003	27,898,500	6
13	Footpath provision passenger side (informal path >1m)	C	5.80 km	0.1	0.8	4.2	39.8	882,960	141,451	6
14	Central median barrier (1+1)	C	34.80 km	4.8	31.5	171.9	1629.9	36,201,352	6,288,200	6
15	Road surface rehabilitation	C	0.80 km	0.0	0.3	1.7	15.9	353,184	70,435	5
16	Improve curve delineation	M	0.40 km	0.1	0.4	2.1	19.9	441,480	7,460	59
17	Sight distance (obstruction removal)	M	1.40 km	0.2	1.5	8.4	79.5	1,765,920	35,280	50
18	Shoulder rumble strips	M	199.30 km	9.8	64.5	352.1	3339.4	74,168,624	2,382,592	31
19	Refuge Island	M	14 sites	1.6	10.8	58.7	556.6	12,361,437	416,422	30
20	Protected turn lane (unsignalised 4 leg)	M	3 sites	1.6	10.8	58.7	556.6	12,361,437	535,399	23
21	Unsignalised crossing	M	5 sites	0.5	3.1	16.8	159.0	3,531,839	217,465	16
22	Central hatching	M	5.70 km	0.1	0.5	2.5	23.9	529,776	34,173	16
23	Parking improvements	M	1.50 km	0.0	0.2	1.3	11.9	264,888	18,900	14
24	Centreline rumble strip / flexi-post	M	1.80 km	0.0	0.2	1.3	11.9	264,888	19,512	14
25	Improve Delineation	M	45.70 km	1.5	10.0	54.5	516.8	11,478,478	847,446	14
26	Protected turn lane (unsignalised 3 leg)	M	54 sites	8.6	56.9	310.2	2941.8	65,339,026	7,210,571	9
27	Wide centreline	M	12.50 km	0.1	0.5	2.5	23.9	529,776	75,710	7
28	Delineation and signing (intersection)	M	8 sites	0.1	0.4	2.1	19.9	441,480	88,582	5
29	Clear roadside hazards - driver side	M	0.10 km	0.0	0.1	0.4	4.0	88,296	20,000	4
30	Shoulder sealing passenger side (>1m)	M	71.50 km	3.4	22.3	121.6	1152.9	25,605,835	6,334,720	4
	Total			**78**	**513**	**2,801**	**26,568**	**590,082,044**	**71,395,898**	

Table 9-3 Budget availability scenarios (Netherlands)

Budget scenario (%)	100	80	60	25
Amount (€)	71,395,898	57,116,718	42,837,539	17,848,975

9.4 Indonesia case study

The Indonesia cases study is part of the BIGRS (2015– 2019) that was aimed at improving road infrastructure in Bandung city. The objective of this project was to improve the road safety condition of the assessed road network (172Km) from a 1 or 2–star rating to a 3–star rating or better standard. According to iRAP, the safest roads are 5– stars (iRAP, 2019), although achieving this is an overwhelming task and is an aspiration for all road safety activists in the future. Therefore, in most cases achieving a 3– star rating on all roads is the minimum acceptable standard in comparison to the least safe roads of 1– star (iRAP, 2019).

BIGRS that was implemented in 10 cities in low and middle-income countries helped these cities to implement a comprehensive package of proven countermeasures within a specified project time so as to improve road safety (Li *et al.,* 2020). Arguably, without categorising these measures during prioritisation and selection, it may be impossible for these projects to achieve economic sustainability. In addition, BIGRS projects focus on a number of other areas such as enforcement, data collection and surveillance, changing road user behaviour and upgrading vehicle road safety (Cliff *et al*., 2019). Therefore, the project resources will never be enough amongst these competing tasks and thus using this case study, this research demonstrated effective use of the available resources using the newly developed model.

9.4.1 Input data

In an effort to further demonstrate the application of the newly developed in a developing country, this research used part of the Bandung infrastructure improvement programme that was modified accordingly. Therefore, this Thesis used this case study to demonstrate how the newly developed model may effectively allocate and prioritise measures based on budget availability. Further analysis of the original data resulted in this input data (Table 9-4) in which a total of $8,203,637 is required to yield economic safety benefits of $28,477,353 after implementation. Similarly, in Table 9-5, 80%, 60% or 25% of the $8,203,637 may be available as part of the project to improve road network safety.

Table 9-4 A programme of countermeasures (Indonesia)

S/N	Countermeasure	Category	Length/ Sites	Fatal	Serious injury	Slight injury	PDO	Economic benefit ($)	Estimated cost ($)	BCR
1	Implement one way network	C	8.70 km	59.1	391.0	2133.5	20234.9	11,611,770	615,759	19
2	Pave road surface	C	1.40 km	3.7	24.6	134.1	1272.1	730,013	109,159	7
3	Central median barrier (no duplication)	C	0.40 km	0.2	1.5	8.4	79.5	45,626	12,268	4
4	Signalise intersection (4-leg)	C	11 sites	5.1	33.8	184.4	1749.2	1,003,768	424,661	2
5	Overtaking lane	C	8.40 km	12.1	79.9	435.9	4134.4	2,372,542	1,189,052	2
6	Pedestrian fencing	C	8.10 km	3.8	25.4	138.3	1311.9	752,826	391,548	2
7	Footpath provision passenger side (>3m from road)	C	8.20 km	6.0	39.9	218.0	2067.2	1,186,271	645,724	2
8	Bicycle Lane (on-road)	C	3.50 km	0.1	0.6	3.4	31.8	18,250	10,670	2
9	Traffic calming	C	25.40 km	30.1	199.0	1085.6	10296.4	5,908,543	3,478,156	2
10	Street lighting (mid-block)	C	1.70 km	0.8	5.4	29.3	278.3	159,690	101,880	2
11	Centreline rumble strip / flexi-post	M	0.20 km	0.3	2.3	12.6	119.3	68,439	1,684	41
12	Central hatching	M	10.30 km	6.4	42.3	230.5	2186.5	1,254,710	43,367	29
13	Sight distance (obstruction removal)	M	0.90 km	1.63	10.8	58.7	556.6	319,381	25,263	13
14	Shoulder rumble strips	M	1.60 km	0.35	2.3	12.6	119.3	68,439	8,982	8
15	Clear roadside hazards (bike lane)	M	1.30 km	0.2	1.5	8.4	79.5	45,626	6,353	7
16	Improve Delineation	M	8.70 km	2.3	15.4	83.8	795.1	456,258	125,920	4
17	Improve curve delineation	M	2.00 km	2.7	17.7	96.4	914.3	524,697	151,676	3
18	Upgrade pedestrian facility quality	M	15 sites	0.2	1.5	8.4	79.5	45,626	14,035	3
19	Refuge Island	M	63 sites	2.8	18.4	100.6	954.1	547,510	176,838	3
20	Unsignalised crossing	M	11 sites	0.5	3.1	16.8	159.0	91,252	30,876	3
21	Delineation and signing (intersection)	M	17 sites	1.4	9.2	50.3	477.1	273,755	122,092	2
22	Skid Resistance (paved road)	M	0.90 km	2.8	18.4	100.6	954.1	547,510	261,982	2
23	Central turning lane full length	M	0.60 km	1.2	7.7	41.9	397.5	228,129	109,548	2
24	Shoulder sealing driver side (>1m)	M	0.30 km	0.1	0.4	2.1	19.9	11,406	7,494	2
25	School zone - crossing guard or supervisor	M	24 sites	1.0	6.9	37.7	357.8	205,316	138,650	1
	Total			**145**	**959**	**5,232**	**49,625**	**28,477,353**	**8,203,637**	

The countermeasures were categorised as capital (C) and maintenance (M) based on life years shown in Table 9-6 using the same categorisation criterion applied in the Netherlands case study. Similarly, the countermeasures as categorised in Table 9-6 are comparable to those included in a capital and maintenance works programmes by Tziotis (2011).

Table 9-5 Budget availability scenarios (Indonesia)

Budget scenario (%)	100	80	60	25
Amount ($)	8,203,637	6,562,909	4,922,182	2,050,909

Table 9-6 Life years of countermeasures (Indonesia)

Countermeasure	Life years	Category	Source of information
Implement one way network	20+	Capital	iRAP, 2022
Pave road surface	10 – 20	Capital	iRAP, 2022
Central median barrier (no duplication)	10 – 30	Capital	PIARC, 2021; iRAP, 2010; Grzyl *et al.,* 2017
Signalise intersection (4-leg)	10 – 20	Capital	iRAP, 2022
Overtaking lane	10 – 20	Capital	iRAP, 2022
Pedestrian fencing	10 – 20	Capital	iRAP, 2010
Footpath provision passenger side (>3m from road)	10 – 20	Capital	iRAP, 2010
Bicycle Lane (on-road)	10 – 25	Capital	Elvik *et al.,* 2009; iRAP, 2010
Traffic calming	10 – 20	Capital	iRAP, 2010
Street lighting (mid-block)	10 – 20	Capital	iRAP, 2010
Signalise intersection (3-leg)	10 – 20	Capital	iRAP, 2022
Footpath provision driver side (>3m from road)	10 – 20	Capital	iRAP, 2010
Footpath provision passenger side (adjacent to road)	10 – 20	Capital	iRAP, 2010
Motorcycle Lane (Segregated)	10 – 20	Capital	iRAP, 2022
Road surface rehabilitation	10 – 20	Capital	iRAP, 2022
Centreline rumble strip / flexi-post	1 – 5	Maintenance	iRAP, 2022
Central hatching	1 – 5	Maintenance	iRAP, 2010
Sight distance (obstruction removal)	5 – 10	Maintenance	iRAP, 2010
Shoulder rumble strips	1 – 5	Maintenance	iRAP, 2010
Clear roadside hazards (bike lane)	5 – 10	Maintenance	iRAP, 2010
Improve Delineation	1 – 5	Maintenance	iRAP, 2010
Improve curve delineation	1 – 5	Maintenance	iRAP, 2010
Upgrade pedestrian facility quality	1 – 5	Maintenance	iRAP, 2022
Refuge Island	5 – 10	Maintenance	iRAP, 2010
Unsignalised crossing	5 – 10	Maintenance	iRAP, 2022
Delineation and signing (intersection)	1 – 5	Maintenance	iRAP, 2010
Skid Resistance (paved road)	5 – 10	Maintenance	iRAP, 2022
Central turning lane full length	1 – 5	Maintenance	iRAP, 2022
Shoulder sealing driver side (>1m)	5 – 10	Maintenance	iRAP, 2022
School zone - crossing guard or supervisor	5 – 10	Maintenance	iRAP, 2022

9.5 Optimisation software

Nowadays, optimisation models can easily be analysed using computer software such as Premium Solver Platform (Jiang, 2010), GAMS (Calasan *et al.,* 2021) and LINGO (LINDO, 2020). The above solvers (commercial and non-commercial) are readily available as free or licence software on the market to solve MILP problems faster using heuristic and branching algorithms. Branch-and-bound technique is one of the known optimisation solution algorithms applied today for solving and obtaining optimal solutions of numerous problems. Specifically, the branch-and-bound algorithm is the standardised procedure for solving MILP problems (Etheve *et al*., 2020). The algorithm divides the optimisation problem into smaller sub problems to obtain an optimal solution or until the sub problem is infeasible.

LINGO that has a remarkable popularity is one the most powerful and friendly software in use today since its inception in the 1980s. A comprehensive and interactive computer software package facilitates the building and solving of optimisation models more easily and efficiently. Accordingly, in this Thesis, LINGO software developed by Linear Interactive and Discrete Optimizer (LINDO) systems with capacity to handle numerous variables and constraints is utilised to run the developed model. LINGO's 'branch–and–bound' technique that applies to optimisation problems subjected to constraints solved the MILP problem. The branch–and–bound technique is faster with ability to handle large sets of data and does not suffer from round off errors as with dynamic programming (Brown, Bulfin and Deason, 1990).

9.6 Summary

In order to demonstrate the practical use of the proposed approach and the newly developed optimisation model, infrastructure improvement programmes developed for the Netherlands and Indonesia are used as case studies. These programmes consist of realistic and effective countermeasures aimed at improving the safety condition of the road network.

The countermeasures in this study were categorised into capital and maintenance, thus the newly developed concept of life span-based optimisation. However, due to budget limitations and competing interests with other policies, there will always be challenges regarding prioritisation and selection of measures. This necessitates the use of this newly developed model in solving the problem of prioritising countermeasures under financial constraints. This research applies three-budget constraint scenarios of 80%, 60% and 25%. The study also makes a comparative study as part of model application by conducting a non-life span optimisation.

To run the developed model, LINGO software, one the most powerful and friendly software in use today since its inception is utilised by this study. The results from the application of the newly developed optimisation procedure based on these two case studies are presented in the next Chapter.

CHAPTER 10: RESULTS FROM THE OPTIMISATION PROCEDURE

10.1 Introduction

The results in this Chapter are the outputs of the newly developed optimisation model applied to prioritise countermeasures in a road network safety programme limited by funds using two case studies. These case studies were chosen by this research to represent road network safety needs for both developed and developing countries so as to draw firm conclusions and demonstrate the wider applicability of the developed model.

The results include the list of countermeasures prioritised, budget allocation and economic benefits in each countermeasure category for the different funding options. In addition, the results also include the total number of crashes reduced or saved in each budget scenario. Firstly, to demonstrate the effect of the change in the prioritisation and selection process due to the proposed optimisation procedure, the study first established the budget allocation and economic benefits with the unconstrained budget scenario (100% budget availability) and constrained budget scenarios based on the life-span categorisation approach. Secondary, the study conducted budget optimisation for both the life span and non-life span-based approaches in all the budget scenarios to clearly demonstrate and document the effect of life span categorisation on prioritisation of measures. Finally, this research conducted a sensitivity analysis to determine the effect of the changes in the availability of crash data on computation of economic benefits and countermeasure selection.

10.2 The Netherlands case study

The Netherlands is the case study in this research with typical road network safety infrastructure needs for a developed country. The results in this section are due to the application of the developed optimisation model to a programme of safety infrastructure countermeasures developed for Utrecht provincial roads using the iRAP methodology.

Table 10-1 shows optimisation results for the proposed life span-based approach under an unconstrained budget together with 3-budget constraint scenarios (80%, 60% and 25% budget availability scenarios). Thus, Table 10-1 shows the unconstrained together with the constrained results in all the budget scenarios. Furthermore, Table 10-1 shows the total number of crashes reduced under each budget scenario starting with the unconstrained scenario (29,960 crashes) and the economic benefits achieved.

Table 10-1 Budget optimisation results (Netherlands)

	Category	Budget (€)	Economic benefits (€)	Budget (%)	Economic benefits (%)
Unconstrained budget (100%)	Capital	53,151,666	380,908,864	74%	65%
	Maintenance	18,244,232	209,173,180	26%	35%
	Total	**71,395,898**	**590,082,044**	**29,960 (100%)**	
Constrained budget (optimisation results)					
A. 80% (€57,116,718)	Capital	46,215,112	340,292,712	81%	67%
	Maintenance	10,897,774	171,117,612	19%	33%
	Total	**57,112,886**	**511,410,324**	**25,966 (87%)**	
B. 60% (€42,837,539)	Capital	24,719,559	201,668,022	58%	49%
	Maintenance	18,116,138	208,378,516	42%	51%
	Total	**42,835,697**	**410,046,538**	**20,819 (69%)**	
C. 25% (€17,848,975)	Capital	6,989,212	87,766,206	39%	34%
	Maintenance	10,839,362	170,499,540	61%	66%
	Total	**17,828,574**	**258,265,746**	**13,113 (44%)**	

In addition, Figure 10.1 shows the total number of crashes reduced due to prioritisation and selection for all the budget scenarios including the unconstrained scenario. The results, as shown in Figure 10.1, indicate that the safety benefits increase with increasing availability of funds and vice versa. The other key observation from the optimisation of this case study is the possibility to reduce approximately 50% of the traffic crashes with only 25% of the budget.

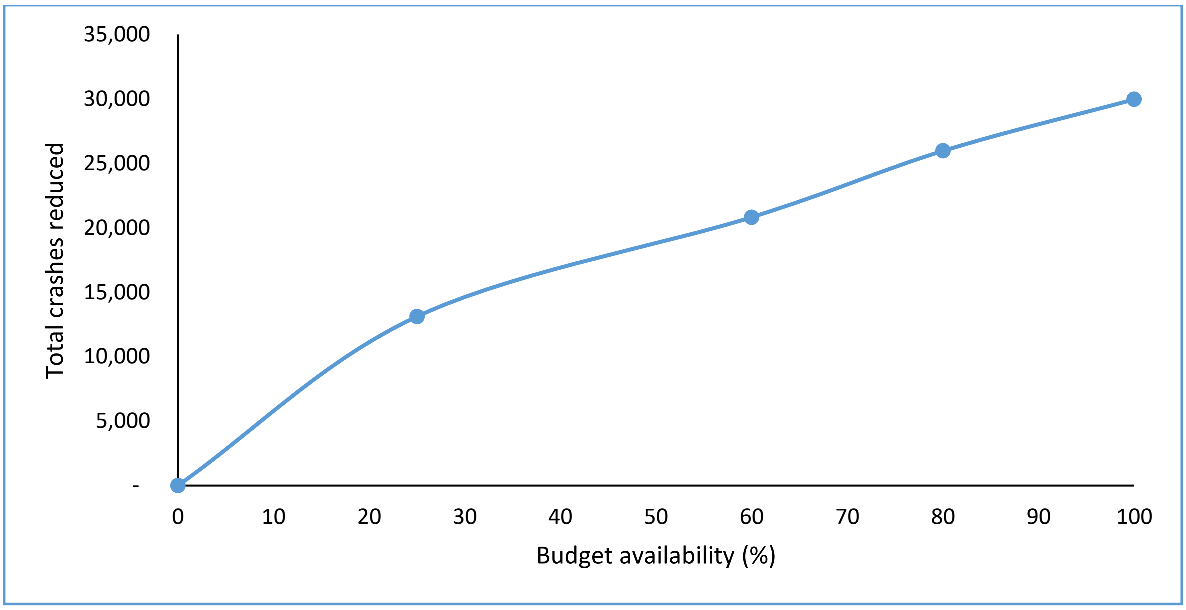


Figure 10.1 Total crash reduction at different budget availability levels (Netherlands)

Furthermore, Figure 10.2 shows the total economic benefits and the benefits due to the allocation of the available funds to capital and maintenance measures. Interestingly, the impact of maintenance on economic benefits is about 30% and is relatively unchanged even when the available budget exceeds 25%. Generally, there is a significant change in economic benefits between capital and maintenance countermeasures when the budget is reduced to 60%. Specifically, economic benefits increase and decrease by over 30% with maintenance and capital countermeasures respectively. Again, as the budget is reduced to 25%, the economic benefits increase and decrease by over 20%.

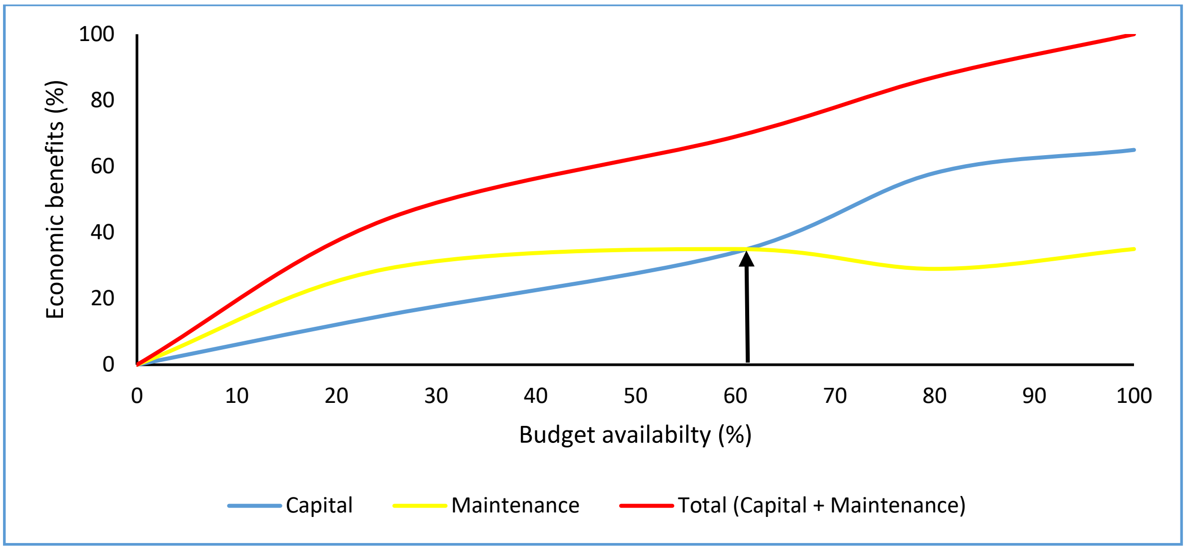


Figure 10.2 Economic benefits at different budget availability levels (Netherlands)

Table 10-3 shows the list of countermeasures selected in the unconstrained budget scenario. Finally, the results in Table 10-4 show the lists of countermeasures prioritised and selected for implementation under the different budget scenarios.

A comparison of these lists shows that the number of countermeasures selected does not depend entirely on the availability of funds. For example, the model selects 24 countermeasures with 60% of the budget compared to 22 countermeasures selected with 80% of the budget. Furthermore, these results show that the effectiveness of a road safety programme increases with increasing budget constraints. The outstanding similarity in Table 10-4 is the consistent selection of the topmost effective countermeasures in all the budget scenarios.

10.2.1 A comparison between life span and non-life span optimisation

The analysis also conducted a non-life span optimisation for all the budget scenarios. Table 10-2 shows the number of countermeasures selected for each of the countermeasure category in these two approaches. It is apparent from the Table that the number of maintenance measures is higher than capital measures in all the budget scenarios. Consequently, in the life span approach, the number of capital measures selected increases while reducing or maintaining the number for maintenance measures. The results as seen in Table 10-2 indicate that a life span-based approach changes the prioritisation and selection of countermeasures.

Table 10-2 Measure selection in life span and non-life span optimisation (Netherlands)

Budget availability	**Countermeasure category**	**Number of countermeasures selected**	
		Non-life span optimisation	Life span optimisation
80% (€57,116,718)	Capital	9	11
	Maintenance	10	11
60% (€42,837,539)	Capital	8	12
	Maintenance	12	12
25% (€17,848,975)	Capital	7	8
	Maintenance	11	8

Table 10-3 Countermeasure selection for unconstrained budget scenario (Netherlands)

S/N	Countermeasure	Category	Length / sites	Crashes minimised				Economic benefits (€)	Costs(€)	BCR
				Fatal	Serious injury	Slight injury	PDO			
1	Signalised crossing	C	1 sites	1.2	7.7	41.9	397.5	8,829,598	45,000	196
2	Pedestrian fencing	C	27.20 km	1.0	6.9	37.7	357.8	7,946,638	179,606	44
3	Street lighting (intersection)	C	14 sites	2.4	16.1	88.0	834.8	18,542,156	504,000	37
4	Traffic calming	C	2.90 km	0.1	0.8	4.2	39.8	882,960	87,581	10
5	Central median barrier (no duplication)	C	0.70 km	0.1	0.8	4.2	39.8	882,960	95,182	9
6	Footpath provision driver side (>3m from road)	C	25.40 km	3.3	21.5	117.4	1113.1	24,722,875	2,922,040	8
7	Footpath provision passenger side (>3m from road)	C	26.80 km	3.4	22.3	121.6	1152.9	25,605,835	3,085,368	8
8	Footpath provision driver side (informal path >1m)	C	4.70 km	0.1	0.8	4.2	39.8	882,960	114,747	8
9	Footpath provision driver side (adjacent to road)	C	27.90 km	4.1	26.9	146.7	1391.4	30,903,593	4,388,280	7
10	Bicycle Lane (off-road)	C	3.50 km	0.3	2.3	12.6	119.3	2,648,879	392,156	7
11	Footpath provision passenger side (adjacent to road)	C	44.10 km	6.0	39.9	218.0	2067.2	45,913,910	6,939,120	7
12	Roadside barriers - driver side	C	206.20 km	23.1	152.9	834.1	7911.1	175,709,003	27,898,500	6
13	Footpath provision passenger side (informal path >1m)	C	5.80 km	0.1	0.8	4.2	39.8	882,960	141,451	6
14	Central median barrier (1+1)	C	34.80 km	4.8	31.5	171.9	1629.9	36,201,352	6,288,200	6
15	Road surface rehabilitation	C	0.80 km	0.0	0.3	1.7	15.9	353,184	70,435	5
16	Improve curve delineation	M	0.40 km	0.1	0.4	2.1	19.9	441,480	7,460	59
17	Sight distance (obstruction removal)	M	1.40 km	0.2	1.5	8.4	79.5	1,765,920	35,280	50
18	Shoulder rumble strips	M	199.30 km	9.8	64.5	352.1	3339.4	74,168,624	2,382,592	31
19	Refuge Island	M	14 sites	1.6	10.8	58.7	556.6	12,361,437	416,422	30
20	Protected turn lane (unsignalised 4 leg)	M	3 sites	1.6	10.8	58.7	556.6	12,361,437	535,399	23
21	Unsignalised crossing	M	5 sites	0.5	3.1	16.8	159.0	3,531,839	217,465	16
22	Central hatching	M	5.70 km	0.1	0.5	2.5	23.9	529,776	34,173	16
23	Parking improvements	M	1.50 km	0.0	0.2	1.3	11.9	264,888	18,900	14
24	Centreline rumble strip / flexi-post	M	1.80 km	0.0	0.2	1.3	11.9	264,888	19,512	14
25	Improve Delineation	M	45.70 km	1.5	10.0	54.5	516.8	11,478,478	847,446	14
26	Protected turn lane (unsignalised 3 leg)	M	54 sites	8.6	56.9	310.2	2941.8	65,339,026	7,210,571	9
27	Wide centreline	M	12.50 km	0.1	0.5	2.5	23.9	529,776	75,710	7
28	Delineation and signing (intersection)	M	8 sites	0.1	0.4	2.1	19.9	441,480	88,582	5
29	Clear roadside hazards - driver side	M	0.10 km	0.0	0.1	0.4	4.0	88,296	20,000	4
30	Shoulder sealing passenger side (>1m)	M	71.50 km	3.4	22.3	121.6	1152.9	25,605,835	6,334,720	4
	Total			**78**	**513**	**2,801**	**26,568**	**590,082,044**	**71,395,898**	

Table 10-4 Countermeasure selection for different budget availability scenarios (Netherlands)

S/N	Countermeasure	Category	Length / sites	Crashes minimised				Economic benefits (€)	Costs(€)	BCR
				Fatal	Serious injury	Slight injury	PDO			
A: 80% Budget availability										
1	Signalised crossing	C	1 sites	1.2	7.7	41.9	397.5	8,829,598	45,000	196
2	Pedestrian fencing	C	27.20 km	1.0	6.9	37.7	357.8	7,946,638	179,606	44
3	Street lighting (intersection)	C	14 sites	2.4	16.1	88.0	834.8	18,542,156	504,000	37
4	Traffic calming	C	2.90 km	0.1	0.8	4.2	39.8	882,960	87,581	10
5	Central median barrier (no duplication)	C	0.70 km	0.1	0.8	4.2	39.8	882,960	95,182	9
6	Footpath provision driver side (>3m from road)	C	25.40 km	3.3	21.5	117.4	1113.1	24,722,875	2,922,040	8
7	Footpath provision passenger side (>3m from road)	C	26.80 km	3.4	22.3	121.6	1152.9	25,605,835	3,085,368	8
8	Footpath provision driver side (adjacent to road)	C	27.90 km	4.1	26.9	146.7	1391.4	30,903,593	4,388,280	7
9	Footpath provision passenger side (adjacent to road)	C	44.10 km	6.0	39.9	218.0	2067.2	45,913,910	6,939,120	7
10	Roadside barriers - driver side	C	206.20 km	23.1	152.9	834.1	7911.1	175,709,003	27,898,500	6
11	Road surface rehabilitation	C	0.80 km	0.0	0.3	1.7	15.9	353,184	70,435	5
12	Improve curve delineation	M	0.40 km	0.1	0.4	2.1	19.9	441,480	7,460	59
13	Sight distance (obstruction removal)	M	1.40 km	0.2	1.5	8.4	79.5	1,765,920	35,280	50
14	Shoulder rumble strips	M	199.30 km	9.8	64.5	352.1	3339.4	74,168,624	2,382,592	31
15	Refuge Island	M	14 sites	1.6	10.8	58.7	556.6	12,361,437	416,422	30
16	Protected turn lane (unsignalised 4 leg)	M	3 sites	1.6	10.8	58.7	556.6	12,361,437	535,399	23
17	Unsignalised crossing	M	5 sites	0.5	3.1	16.8	159.0	3,531,839	217,465	16
18	Central hatching	M	5.70 km	0.1	0.5	2.5	23.9	529,776	34,173	16
19	Parking improvements	M	1.50 km	0.0	0.2	1.3	11.9	264,888	18,900	14
20	Centreline rumble strip / flexi-post	M	1.80 km	0.0	0.2	1.3	11.9	264,888	19,512	14
21	Protected turn lane (unsignalised 3 leg)	M	54 sites	8.6	56.9	310.2	2941.8	65,339,026	7,210,571	9
22	Clear roadside hazards - driver side	M	0.10 km	0.0	0.1	0.4	4.0	88,296	20,000	4
	Total			**67**	**445**	**2,428**	**23,026**	**511,410,324**	**57,112,886**	
B: 60% Budget availability										
1	Signalised crossing	C	1 sites	1.2	7.7	41.9	397.5	8,829,598	45,000	196
2	Pedestrian fencing	C	27.20 km	1.0	6.9	37.7	357.8	7,946,638	179,606	44
3	Street lighting (intersection)	C	14 sites	2.4	16.1	88.0	834.8	18,542,156	504,000	37
4	Traffic calming	C	2.90 km	0.1	0.8	4.2	39.8	882,960	87,581	10
5	Central median barrier (no duplication)	C	0.70 km	0.1	0.8	4.2	39.8	882,960	95,182	9
6	Footpath provision driver side (>3m from road)	C	25.40 km	3.3	21.5	117.4	1113.1	24,722,875	2,922,040	8
7	Footpath provision passenger side (>3m from road)	C	26.80 km	3.4	22.3	121.6	1152.9	25,605,835	3,085,368	8
8	Footpath provision driver side (informal path >1m)	C	4.70 km	0.1	0.8	4.2	39.8	882,960	114,747	8
9	Footpath provision driver side (adjacent to road)	C	27.90 km	4.1	26.9	146.7	1391.4	30,903,593	4,388,280	7
10	Footpath provision passenger side (adjacent to road)	C	44.10 km	6.0	39.9	218.0	2067.2	45,913,910	6,939,120	7
11	Central median barrier (1+1)	C	34.80 km	4.8	31.5	171.9	1629.9	36,201,352	6,288,200	6
12	Road surface rehabilitation	C	0.80 km	0.0	0.3	1.7	15.9	353,184	70,435	5
13	Improve curve delineation	M	0.40 km	0.1	0.4	2.1	19.9	441,480	7,460	59
14	Sight distance (obstruction removal)	M	1.40 km	0.2	1.5	8.4	79.5	1,765,920	35,280	50
15	Shoulder rumble strips	M	199.30 km	9.8	64.5	352.1	3339.4	74,168,624	2,382,592	31
16	Refuge Island	M	14 sites	1.6	10.8	58.7	556.6	12,361,437	416,422	30
17	Protected turn lane (unsignalised 4 leg)	M	3 sites	1.6	10.8	58.7	556.6	12,361,437	535,399	23
18	Unsignalised crossing	M	5 sites	0.5	3.1	16.8	159.0	3,531,839	217,465	16
19	Central hatching	M	5.70 km	0.1	0.5	2.5	23.9	529,776	34,173	16
20	Parking improvements	M	1.50 km	0.0	0.2	1.3	11.9	264,888	18,900	14
21	Improve Delineation	M	45.70 km	1.5	10.0	54.5	516.8	11,478,478	847,446	14
22	Protected turn lane (unsignalised 3 leg)	M	54 sites	8.6	56.9	310.2	2941.8	65,339,026	7,210,571	9
23	Wide centreline	M	12.50 km	0.1	0.5	2.5	23.9	529,776	75,710	7
24	Shoulder sealing passenger side (>1m)	M	71.50 km	3.4	22.3	121.6	1152.9	25,605,835	6,334,720	4
	Total			**54**	**357**	**1,947**	**18,462**	**410,046,538**	**42,835,697**	
C: 25% Budget availability										
1	Signalised crossing	C	1 sites	1.2	7.7	41.9	397.5	8,829,598	45,000	196
2	Pedestrian fencing	C	27.20 km	1.0	6.9	37.7	357.8	7,946,638	179,606	44
3	Street lighting (intersection)	C	14 sites	2.4	16.1	88.0	834.8	18,542,156	504,000	37
4	Traffic calming	C	2.90 km	0.1	0.8	4.2	39.8	882,960	87,581	10
5	Central median barrier (no duplication)	C	0.70 km	0.1	0.8	4.2	39.8	882,960	95,182	9
6	Footpath provision driver side (>3m from road)	C	25.40 km	3.3	21.5	117.4	1113.1	24,722,875	2,922,040	8
7	Footpath provision passenger side (>3m from road)	C	26.80 km	3.4	22.3	121.6	1152.9	25,605,835	3,085,368	8
8	Road surface rehabilitation	C	0.80 km	0.0	0.3	1.7	15.9	353,184	70,435	5
9	Improve curve delineation	M	0.40 km	0.1	0.4	2.1	19.9	441,480	7,460	59
10	Sight distance (obstruction removal)	M	1.40 km	0.2	1.5	8.4	79.5	1,765,920	35,280	50
11	Shoulder rumble strips	M	199.30 km	9.8	64.5	352.1	3339.4	74,168,624	2,382,592	31
12	Refuge Island	M	14 sites	1.6	10.8	58.7	556.6	12,361,437	416,422	30
13	Protected turn lane (unsignalised 4 leg)	M	3 sites	1.6	10.8	58.7	556.6	12,361,437	535,399	23
14	Unsignalised crossing	M	5 sites	0.5	3.1	16.8	159.0	3,531,839	217,465	16
15	Central hatching	M	5.70 km	0.1	0.5	2.5	23.9	529,776	34,173	16
16	Protected turn lane (unsignalised 3 leg)	M	54 sites	8.6	56.9	310.2	2941.8	65,339,026	7,210,571	9
	Total			**34**	**225**	**1,226**	**11,628**	**258,265,746**	**17,828,574**	

10.3 Indonesia case study

This second case study has typical road network safety needs from a developing country. Thus, Table 10-5 shows the results from the application of the developed optimisation model to a programme of infrastructure countermeasures developed for Bandung city using iRAP methodology.

Firstly, in the unconstrained budget scenario, 85% and 15% of the budget is allocated to capital and maintenance countermeasures respectively. Secondly, the results further indicate a higher allocation of funds to capital countermeasures than maintenance countermeasures in all budget scenarios. It may be observed from Table 10-5 that it is possible to eliminate over 50% (34,107 crashes) of the existing traffic crashes (55,962) with 25% of the budget.

Table 10-5 Budget optimisation results (Indonesia)

	Category	Budget ($)	Economic benefits ($)	Budget (%)	Economic benefits (%)
Unconstrained budget (100%)	Capital	6,978,876	23,789,301	85%	84%
	Maintenance	1,224,761	4,688,053	15%	16%
	Total	**8,203,637**	**28,477,353**	**55,962 (100%)**	
Constrained budget (optimisation results)					
A. 80% ($6,562,909)	Capital	5,839,725	21,690,513	89%	85%
	Maintenance	714,581	3,707,098	11%	15%
	Total	**6,554,305**	**25,397,611**	**49,909 (89%)**	
B. 60% ($4,922,182)	Capital	3,500,720	17,880,757	74%	79%
	Maintenance	1,217,267	4,676,646	26%	21%
	Total	**4,717,986**	**22,557,404**	**44,328 (79%)**	
C. 25% ($2,050,909)	Capital	1,274,397	13,569,118	62%	78%
	Maintenance	771,723	3,786,943	38%	22%
	Total	**2,046,120**	**17,356,060**	**34,107 (61%)**	

Figure 10.3 shows the economic benefits resulting from the prioritisation and selection of countermeasures in this case study. In particular, the results show the total economic benefits and the benefits from each of the different categories of measures. This also includes for the unconstrained budget scenario. It may be observed that the impact of maintenance countermeasures on economic benefits is about 15% and appears relatively unchanged for budgets above 25%. The economic benefits due to capital measures are higher than maintenance measures in all budget scenarios.

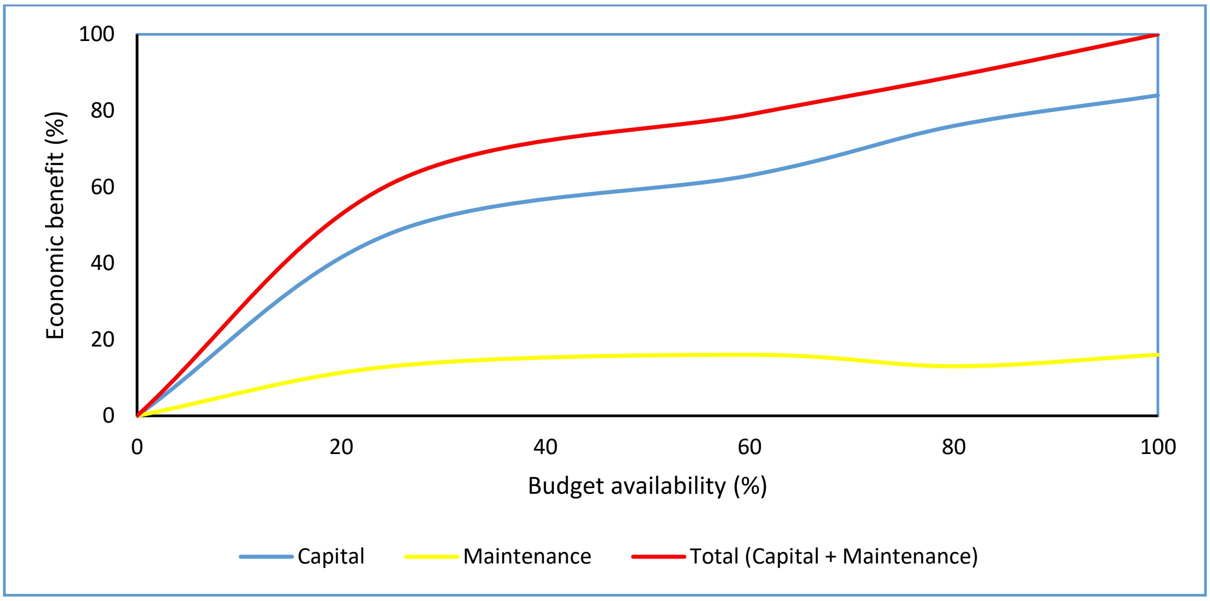


Figure 10.3 Economic benefits at different budget availability levels (Indonesia)

The list of countermeasures selected under the unconstrained budget scenario is shown in Table 10-6. Table 10-8 shows the list of countermeasures prioritised and selected under each budget scenario. There is an interesting observation regarding the number and composition of countermeasures selected from this Table. As an example, with the 80% and 60% budget availability, the model selects 19 and 23 countermeasures respectively. Similarly, not all the countermeasures selected with 60% of the budget are included in the 80% budget availability selection.

The key similarity is the selection of the same topmost cost-effective countermeasures in all the budget scenarios. In Table 10-8, there is also a clear trend of increasing utilisation of available funds and programme effectiveness with increasing budget constraints.

Table 10-6 Countermeasure selection for unconstrained budget scenario (Indonesia)

S/N	Countermeasure	Category	Length/ Sites	Fatal	Serious injury	Slight injury	PDO	Economic benefit ($)	Estimated cost ($)	BCR
1	Implement one way network	C	8.70 km	59.1	391.0	2133.5	20234.9	11,611,770	615,759	19
2	Pave road surface	C	1.40 km	3.7	24.6	134.1	1272.1	730,013	109,159	7
3	Central median barrier (no duplication)	C	0.40 km	0.2	1.5	8.4	79.5	45,626	12,268	4
4	Signalise intersection (4-leg)	C	11 sites	5.1	33.8	184.4	1749.2	1,003,768	424,661	2
5	Overtaking lane	C	8.40 km	12.1	79.9	435.9	4134.4	2,372,542	1,189,052	2
6	Pedestrian fencing	C	8.10 km	3.8	25.4	138.3	1311.9	752,826	391,548	2
7	Footpath provision passenger side (>3m from road)	C	8.20 km	6.0	39.9	218.0	2067.2	1,186,271	645,724	2
8	Bicycle Lane (on-road)	C	3.50 km	0.1	0.6	3.4	31.8	18,250	10,670	2
9	Traffic calming	C	25.40 km	30.1	199.0	1085.6	10296.4	5,908,543	3,478,156	2
10	Street lighting (mid-block)	C	1.70 km	0.8	5.4	29.3	278.3	159,690	101,880	2
11	Centreline rumble strip / flexi-post	M	0.20 km	0.3	2.3	12.6	119.3	68,439	1,684	41
12	Central hatching	M	10.30 km	6.4	42.3	230.5	2186.5	1,254,710	43,367	29
13	Sight distance (obstruction removal)	M	0.90 km	1.63	10.8	58.7	556.6	319,381	25,263	13
14	Shoulder rumble strips	M	1.60 km	0.35	2.3	12.6	119.3	68,439	8,982	8
15	Clear roadside hazards (bike lane)	M	1.30 km	0.2	1.5	8.4	79.5	45,626	6,353	7
16	Improve Delineation	M	8.70 km	2.3	15.4	83.8	795.1	456,258	125,920	4
17	Improve curve delineation	M	2.00 km	2.7	17.7	96.4	914.3	524,697	151,676	3
18	Upgrade pedestrian facility quality	M	15 sites	0.2	1.5	8.4	79.5	45,626	14,035	3
19	Refuge Island	M	63 sites	2.8	18.4	100.6	954.1	547,510	176,838	3
20	Unsignalised crossing	M	11 sites	0.5	3.1	16.8	159.0	91,252	30,876	3
21	Delineation and signing (intersection)	M	17 sites	1.4	9.2	50.3	477.1	273,755	122,092	2
22	Skid Resistance (paved road)	M	0.90 km	2.8	18.4	100.6	954.1	547,510	261,982	2
23	Central turning lane full length	M	0.60 km	1.2	7.7	41.9	397.5	228,129	109,548	2
24	Shoulder sealing driver side (>1m)	M	0.30 km	0.1	0.4	2.1	19.9	11,406	7,494	2
25	School zone - crossing guard or supervisor	M	24 sites	1.0	6.9	37.7	357.8	205,316	138,650	1
	Total			**145**	**959**	**5,232**	**49,625**	**28,477,353**	**8,203,637**	

10.3.1 A comparison between life span and non-life span optimisation

The study conducted a non-life span-based budget optimisation to compare with the proposed technique of categorising countermeasures during optimisation. Therefore, the results in Table 10-7 include a comparison made in the application of these approaches to the case study. Specifically, Table 10-7 shows the number of countermeasures in each category selected for implementation in each of the approaches in the different budget scenarios.

A comparison of these approaches reveals that in non-life span optimisation, the number of maintenance measures is higher than capital measures. Clearly, there are some changes in the selection of measures. For instance, in life span optimisation, the number of maintenance measures reduces in comparison to those in non-life span optimisation in all budget scenarios. Interestingly, when the available budget is 25%, the capital measures increase from 5 to 6 measures while the maintenance measures reduce from 12 to 10.

10.4 A comparison between Netherlands and Indonesia case studies

This section presents a comparison of the results between the two case studies concerning the number of crashes reduced, the application of different approaches, budget allocation and economic benefits due to prioritisation and selection of measures in each case study. The most interesting similarity in these case studies is the higher number of maintenance measures selected for implementation compared to capital countermeasures in non-life span optimisation (Table 10-2 and Table 10-7). The other key similarity shows that below 80% of the budget, the allocation to capital measures decreases with increasing budget constraints (Figure 10.4). However, the budget allocation to maintenance countermeasures increases with increasing budget constraints (Figure 10.5).

Table 10-7 Measure selection in life span and non-life span optimisation (Indonesia)

Budget availability	Countermeasure category	Number of measures selected	
		Non-life span optimisation	Life span optimisation
80% ($6,562,909)	Capital	7	7
	Maintenace	12	12
60% ($4,922,182)	Capital	9	9
	Maintenace	15	14
25% ($2,050,909)	Capital	5	6
	Maintenace	12	10

Table 10-8 Countermeasure selection for different budget availability scenarios (Indonesia)

S/N	Countermeasure	Category	Length/ Sites	Crashes minimised				Safety benefits ($)	Costs ($)	BCR
				Fatal	Serious injury	Slight injury	PDO			
A: 80% Budget availability										
1	Implement one way network	C	8.70 km	59.1	391.0	2133.5	20234.9	11,611,770	615,759	19
2	Pave road surface	C	1.40 km	3.7	24.6	134.1	1272.1	730,013	109,159	7
3	Central median barrier (no duplication)	C	0.40 km	0.2	1.5	8.4	79.5	45,626	12,268	4
4	Signalise intersection (4-leg)	C	11 sites	5.1	33.8	184.4	1749.2	1,003,768	424,661	2
5	Overtaking lane	C	8.40 km	12.1	79.9	435.9	4134.4	2,372,542	1,189,052	2
6	Bicycle Lane (on-road)	C	3.50 km	0.1	0.6	3.4	31.8	18,250	10,670	2
7	Traffic calming	C	25.40 km	30.1	199.0	1085.6	10296.4	5,908,543	3,478,156	2
8	Centreline rumble strip / flexi-post	M	0.20 km	0.3	2.3	12.6	119.3	68,439	1,684	41
9	Central hatching	M	10.30 km	6.4	42.3	230.5	2186.5	1,254,710	43,367	29
10	Sight distance (obstruction removal)	M	0.90 km	1.6	10.8	58.7	556.6	319,381	25,263	13
11	Shoulder rumble strips	M	1.60 km	0.3	2.3	12.6	119.3	68,439	8,982	8
12	Clear roadside hazards (bike lane)	M	1.30 km	0.2	1.5	8.4	79.5	45,626	6,353	7
13	Improve Delineation	M	8.70 km	2.3	15.4	83.8	795.1	456,258	125,920	4
14	Improve curve delineation	M	2.00 km	2.7	17.7	96.4	914.3	524,697	151,676	3
15	Upgrade pedestrian facility quality	M	15 sites	0.2	1.5	8.4	79.5	45,626	14,035	3
16	Refuge Island	M	63 sites	2.8	18.4	100.6	954.1	547,510	176,838	3
17	Unsignalised crossing	M	11 sites	0.5	3.1	16.8	159.0	91,252	30,876	3
18	Delineation and signing (intersection)	M	17 sites	1.4	9.2	50.3	477.1	273,755	122,092	2
19	Shoulder sealing driver side (>1m)	M	0.30 km	0.1	0.4	2.1	19.9	11,406	7,494	2
	Total			**129**	**855**	**4,666**	**44,258**	**25,397,611**	**6,554,305**	
B: 60% Budget availability										
1	Implement one way network	C	8.70 km	59.1	391.0	2133.5	20234.9	11,611,770	615,759	19
2	Pave road surface	C	1.40 km	3.7	24.6	134.1	1272.1	730,013	109,159	7
3	Central median barrier (no duplication)	C	0.40 km	0.2	1.5	8.4	79.5	45,626	12,268	4
4	Signalise intersection (4-leg)	C	11 sites	5.1	33.8	184.4	1749.2	1,003,768	424,661	2
5	Overtaking lane	C	8.40 km	12.1	79.9	435.9	4134.4	2,372,542	1,189,052	2
6	Pedestrian fencing	C	8.10 km	3.8	25.4	138.3	1311.9	752,826	391,548	2
7	Footpath provision passenger side (>3m from road)	C	8.20 km	6.0	39.9	218.0	2067.2	1,186,271	645,724	2
8	Bicycle Lane (on-road)	C	3.50 km	0.1	0.6	3.4	31.8	18,250	10,670	2
9	Street lighting (mid-block)	C	1.70 km	0.8	5.4	29.3	278.3	159,690	101,880	2
10	Centreline rumble strip / flexi-post	M	0.20 km	0.3	2.3	12.6	119.3	68,439	1,684	41
11	Central hatching	M	10.30 km	6.4	42.3	230.5	2186.5	1,254,710	43,367	29
12	Sight distance (obstruction removal)	M	0.90 km	1.6	10.8	58.7	556.6	319,381	25,263	13
13	Shoulder rumble strips	M	1.60 km	0.3	2.3	12.6	119.3	68,439	8,982	8
14	Clear roadside hazards (bike lane)	M	1.30 km	0.2	1.5	8.4	79.5	45,626	6,353	7
15	Improve Delineation	M	8.70 km	2.3	15.4	83.8	795.1	456,258	125,920	4
16	Improve curve delineation	M	2.00 km	2.7	17.7	96.4	914.3	524,697	151,676	3
17	Upgrade pedestrian facility quality	M	15 sites	0.2	1.5	8.4	79.5	45,626	14,035	3
18	Refuge Island	M	63 sites	2.8	18.4	100.6	954.1	547,510	176,838	3
19	Unsignalised crossing	M	11 sites	0.5	3.1	16.8	159.0	91,252	30,876	3
20	Delineation and signing (intersection)	M	17 sites	1.4	9.2	50.3	477.1	273,755	122,092	2
21	Skid Resistance (paved road)	M	0.90 km	2.8	18.4	100.6	954.1	547,510	261,982	2
22	Central turning lane full length	M	0.60 km	1.2	7.7	41.9	397.5	228,129	109,548	2
23	School zone - crossing guard or supervisor	M	24 sites	1.0	6.9	37.7	357.8	205,316	138,650	1
	Total			**115**	**760**	**4,145**	**39,309**	**22,557,404**	**4,717,986**	
C: 25% Budget availability										
1	Implement one way network	C	8.70 km	59.1	391.0	2133.5	20234.9	11,611,770	615,759	19
2	Pave road surface	C	1.40 km	3.7	24.6	134.1	1272.1	730,013	109,159	7
3	Central median barrier (no duplication)	C	0.40 km	0.2	1.5	8.4	79.5	45,626	12,268	4
4	Signalise intersection (4-leg)	C	11 sites	5.1	33.8	184.4	1749.2	1,003,768	424,661	2
5	Bicycle Lane (on-road)	C	3.50 km	0.1	0.6	3.4	31.8	18,250	10,670	2
6	Street lighting (mid-block)	C	1.70 km	0.8	5.4	29.3	278.3	159,690	101,880	2
7	Centreline rumble strip / flexi-post	M	0.20 km	0.3	2.3	12.6	119.3	68,439	1,684	41
8	Central hatching	M	10.30 km	6.4	42.3	230.5	2186.5	1,254,710	43,367	29
9	Sight distance (obstruction removal)	M	0.90 km	1.6	10.8	58.7	556.6	319,381	25,263	13
10	Shoulder rumble strips	M	1.60 km	0.3	2.3	12.6	119.3	68,439	8,982	8
11	Clear roadside hazards (bike lane)	M	1.30 km	0.2	1.5	8.4	79.5	45,626	6,353	7
12	Improve Delineation	M	8.70 km	2.3	15.4	83.8	795.1	456,258	125,920	4
13	Improve curve delineation	M	2.00 km	2.7	17.7	96.4	914.3	524,697	151,676	3
14	Refuge Island	M	63 sites	2.8	18.4	100.6	954.1	547,510	176,838	3
15	Delineation and signing (intersection)	M	17 sites	1.4	9.2	50.3	477.1	273,755	122,092	2
16	Central turning lane full length	M	0.60 km	1.2	7.7	41.9	397.5	228,129	109,548	2
	Total			**88**	**584**	**3,189**	**30,245**	**17,356,060**	**2,046,120**	

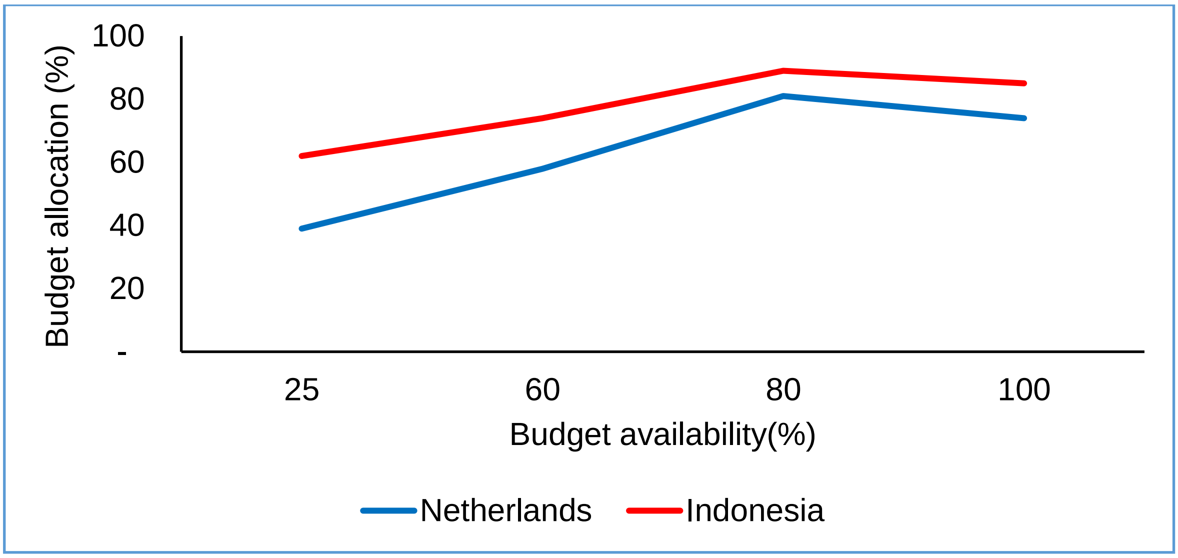


Figure 10.4 A comparison of budget allocation in capital measures

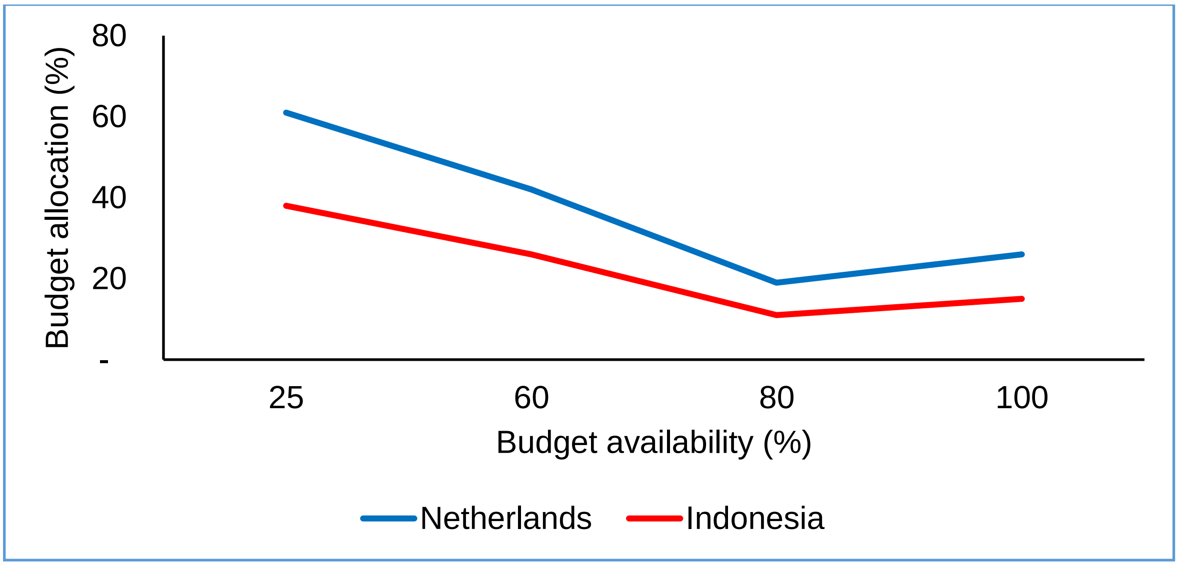


Figure 10.5 A comparison of budget allocation in maintenance measures

In Figure 10.6, the effects of budget availability on crash reduction is similar in both case studies. There is a strong relationship between the total number of crashes reduced and budget availability. A comparison of these results reveals consistency across all the budget scenarios in all the case studies.

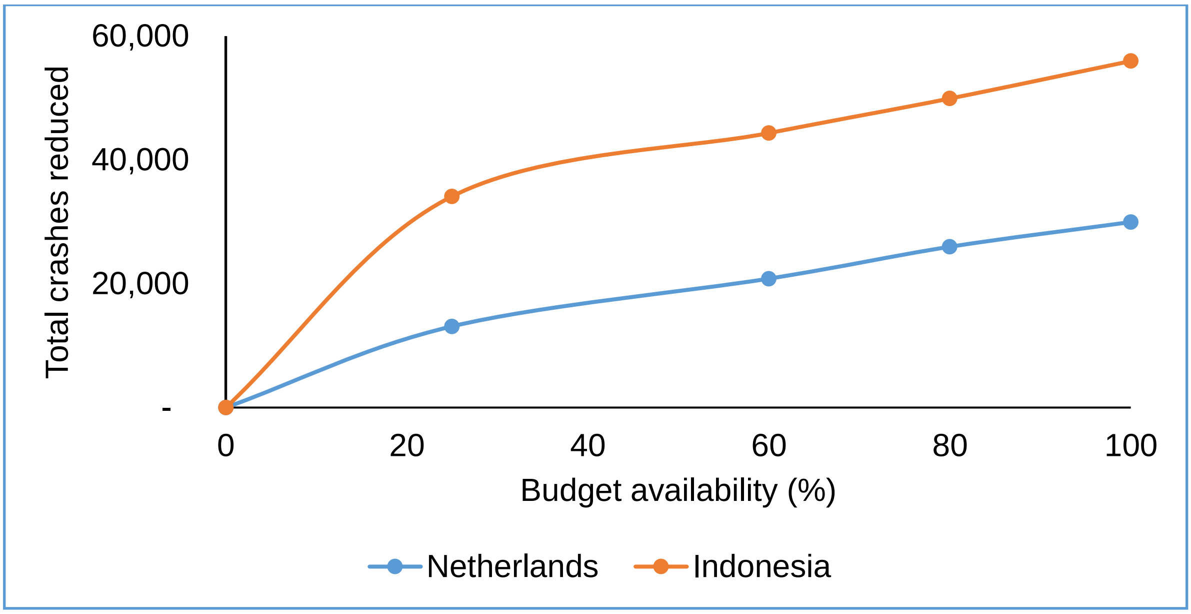


Figure 10.6 A comparison of crash reduction in the case studies

Comparing the results between these two case studies shows a key difference regarding the economic benefits due to capital and maintenance measures. Firstly, the economic benefits due to capital measures are high in Indonesia than in the Netherlands (Figure 10.7). Secondary, the economic benefits due to maintenance measures are high in the Netherlands than in Indonesia (Figure 10.8) in all budget scenarios. Despite this, there is a key similarity where at 80% of the budget, the economic benefits increase and decrease in maintenance and capital measures respectively with increasing budget constraints.

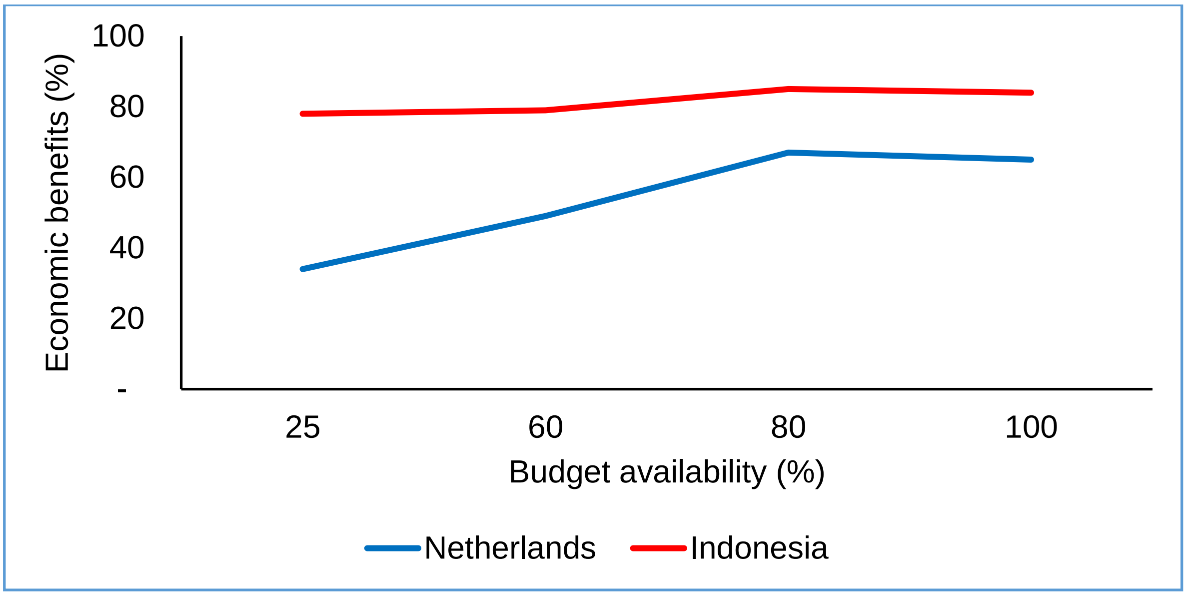


Figure 10.7 A comparison of economic benefits in capital measures

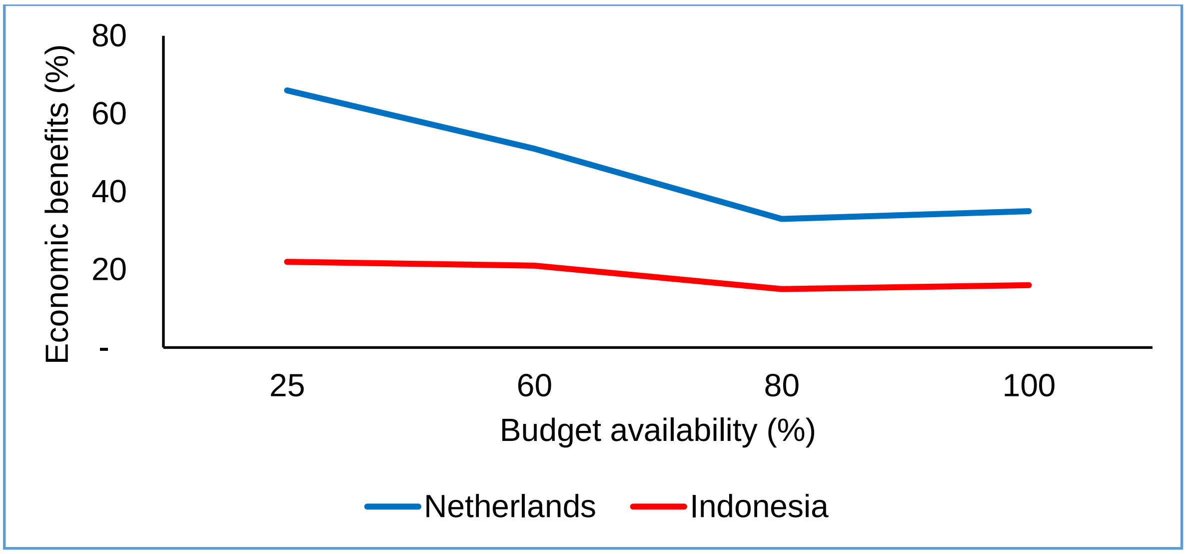
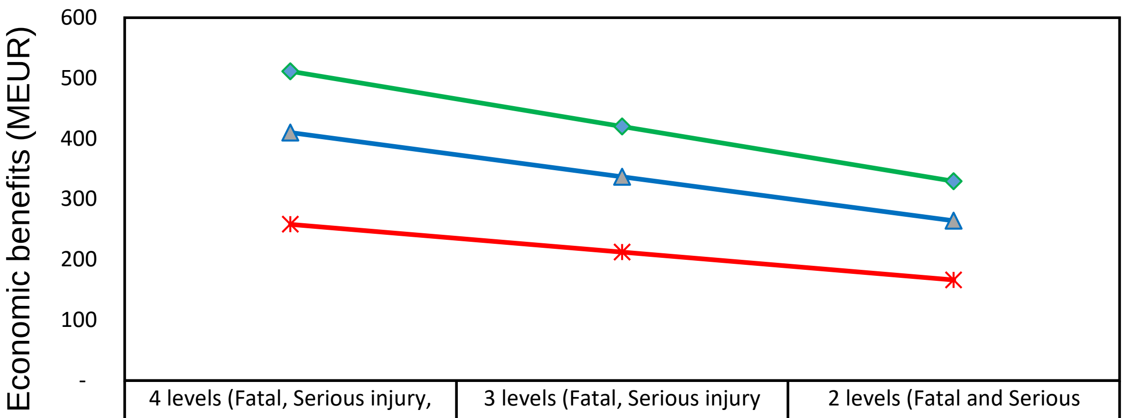


Figure 10.8 A comparison of economic benefits in maintenance measures

10.5 Sensitivity analysis

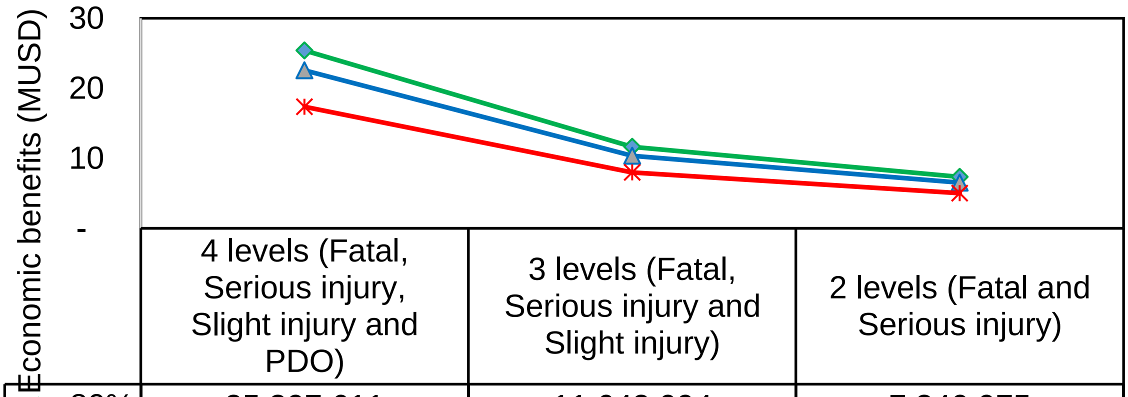
Further to the above a further investigation was carried out to determine the variation in model outputs (resource allocation and prioritisation of countermeasures) through changes made in crash severity levels. This sensitivity was conducted to determine the possibility and effect of conducting the developed optimisation procedure without all the crash severity level data or in the absence of some severity unit rates. For instance, in some countries data regarding slight injuries and PDO crashes and their respective unit rates is limited. Specifically, two sensitivity analyses were conducted for 3 (serious, slight and PDO) and 2 (fatal and serious injury) crash data severity levels respectively to determine the magnitude of the change in the outputs.

The results from sensitivity analyses from both case studies (Figure 10.9 and Figure 10.10) show that the economic benefits vary with changes in the severity levels considered. Furthermore, the results showed that changes in crash severity levels considered do not change the prioritisation and selection of countermeasures. However, the effect of the changes in crash severity levels on the computed economic benefits is higher in Indonesia than that in the Netherlands as per Figure 10.9 and Figure 10.10.



	4 levels (Fatal, Serious injury, Slight injury and PDO)	3 levels (Fatal, Serious injury and Slight injury)	2 levels (Fatal and Serious injury)
80%	511,410,324	420,251,701	329,599,292
60%	410,046,538	336,955,957	264,271,255
25%	258,265,746	212,230,011	166,449,918

Figure 10.9 Sensitivity analysis conducted at different crash severity levels (Netherlands)



	4 levels (Fatal, Serious injury, Slight injury and PDO)	3 levels (Fatal, Serious injury and Slight injury)	2 levels (Fatal and Serious injury)
80%	25,397,611	11,642,094	7,340,075
60%	22,557,404	10,340,162	6,519,237
25%	17,356,060	7,955,901	5,016,015

Figure 10.10 Sensitivity analysis conducted at different crash severity levels (Indonesia)

10.6 Discussion

This research aimed at developing a budget optimisation model to prioritise and select road safety infrastructure countermeasures in a road safety programme constrained financially. The effectiveness of a road safety programme highly depends on the optimum mix between capital and maintenance measures which is the output of a formal optimisation procedure that considers the life span of countermeasures together with their economic benefits. No previously developed budget optimisation models had categorised countermeasures during the prioritisation process.

Therefore, this research developed a novel technique that prioritises road safety countermeasures by considering their effectiveness over their life span together with budget constraints, based on a mixed integer linear programming model with an objective function to maximise their economic safety benefits. Specifically, the procedure categorised individual countermeasures in a road safety investment programme as either capital or maintenance before conducting budget optimisation.

To demonstrate the advantages, impact and the application of this procedure in road network safety investment programmes, two case studies were applied in this research. The results seem to suggest that the newly developed model enhances the conventional non-life span approach due to an improved mix between capital and maintenance programmes for road safety. Consequently, an optimum mix between capital and maintenance measures was obtained as the output of this procedure. The outputs of this procedure based on these case studies is discussed below.

10.6.1 The Netherlands case study

The results show that the balance between capital and maintenance measures changes significantly as per allocation of resources and the resulting economic benefits in comparison to the unconstrained scenario. For instance, in the unconstrained budget, 74% and 26% of the total budget is required for capital and maintenance measures respectively. However, in a constrained budget scenario, capital measures are allocated more and less money for higher and lower percentages of the available budget respectively compared to maintenance measures. As an example, with 25% of the budget available, the model allocates approximately 40% and 60% to capital and maintenance measures respectively. This is where the model demonstrates its logic in the allocation of resources.

This research provides a new insight into the relationship between these categories of countermeasures. The importance of these two categories of measures varies with budget constraints. The results suggest that the importance of capital and maintenance measures decrease and increase respectively with increasing budget constraints. As may be seen from Table 10-1, the resulting economic benefits clearly demonstrate the above. The economic benefits are high and low for capital and maintenance measures respectively for funds above 60% of the budget (Figure 10.2). Correspondingly, for funding availability below 60% of the budget, the economic benefits due to capital measures diminish in comparison to maintenance measures. For this reason, a separate programme dedicated to capital measures is prudent and prioritisation of maintenance measures would be more effective.

The model outputs appear to be consistent with the expected high safety standards of Utrecht where maintenance measures may suffice to keep and maintain the infrastructure in a safe condition in a constrained budget without necessarily investing in capital measures. This could have been the same strategy for Greece in 2005 where short-term interventions had the largest share of the safety budgets (Yannis, Evgenikos and Papadimitriou, 2008).

These results provide an important insight into the road safety requirements for developed countries most especially under budget constraints. In general, therefore, it seems that maintenance measures are more important in developed countries most especially under budget constraints. Furthermore, the results show that the number of countermeasures selected for implementation is dependent on the best mix that maximises economic benefits for any funds available. As may be observed, the model selected 22 countermeasures with 80% of the budget in comparison to 24 countermeasures for the 60% availability (Table 10-4). The model outputs are reasonable and logical for this case study as revealed by the 16 countermeasures (Table 10-4) selected with 25% availability that produce the lowest cost effectiveness ratio.

This model provides a solution to the earlier challenge identified by Elvik (2014) of obtaining the best mix between these two categories of countermeasures more so in a financial constraint. Generally, maintenance measures in this case study appear to be more cost effective than capital measures in all budget scenarios.

The results of this study agree and provide evidence for previous claims that short-term measures are more effective than long-term measures in tackling the road traffic crashes (OECD, 2012; Yannis, Kondyli and Georgopoulou, 2014). However, the results in this research have further demonstrated that countries with a relatively good road infrastructure may put more emphasis on maintenance measures more especially under budget constraints.

Furthermore, the results contribute to a clear understanding that without categorising countermeasures, the selection process is biased thus affecting the effectiveness of the entire road safety programme most especially under financial constraints. Relatedly, these results suggest that without taking into account the varying categories of measures, any other prioritisation and selection process may produce biased results in favour of maintenance measures. Indeed, this life span categorisation approach guarantees and improves the integration between different categories of measures.

The study further demonstrates the effect of categorising measures on the prioritisation and selection process by conducting non-life span optimisation. Unlike non-life span optimisation, life span-based optimisation changes prioritisation and selection of countermeasures. In addition, a life span-based optimisation approach is more effective in the utilisation of the available funds than a non-life span optimisation. There are significant changes in prioritisation and budget utilisation in both approaches as seen in Table 10-2.

The results show that the number of measures selected for implementation is higher in the 80% and 60% budget scenarios when compared to the non-life span approach. Definitely, for the same cost and economic benefits achieved, such an approach offering the highest number of measures might be preferred due to a number of reasons. For instance, considering the numbers, a programme of 22 countermeasures might be more effective compared to that of 19 due to increased complementary. In addition, in the non-life span approach; there are more maintenance than capital measures selected for implementation. Indeed, this clearly indicates the possibility of a biased selection in the absence of categorisation. The major disadvantage with such a biased selection is the preclusion of certain measures that might improve the programme effectiveness most especially with limited funding of the safety budget. Interestingly, there are no significant changes regarding the economic benefits in both approaches for all budget scenarios. However, there is more guarantee and sustainability of the assumed economic safety benefits with the life span approach due to an improved mix between the two categories. Ultimately, the implementation of road safety infrastructure programmes based on this approach may enhance economic growth. This is possible due to efficient utilisation of the available resources coupled with a sustained reduction in road traffic crashes.

10.6.2 Indonesia case study

The results in Table 10-5 show that the allocation of the available resources between capital and maintenance measures changes significantly.

Firstly, the most important relevant finding in this case study is the allocation of more resources to capital than maintenance measures in all budget scenarios. A possible explanation for this might be a poor safety condition for Bandung Road network that possibly requires major improvements and modifications in terms of capital than maintenance measures. These findings may help to understand and give a wider picture of the road network requirements in most developing countries. In addition, they may suggest that developing countries should put emphasis on capital than maintenance measures, as they appear substantial in improving road safety. For instance, with this case study, there are insignificant changes in economic benefits due to allocation of more resources to maintenance countermeasures (Figure 10.3). In fact, with increasing budget constraints, the increasing effectiveness of capital measures shows their importance in a road network safety investment programme. Nonetheless, the trend shows that budget allocation decreases and increases for capital and maintenance measures respectively as the available budget reduces. A possible explanation for this might be the limited choice of the fewer number of capital measures in the case study compared to maintenance measures.

These results suggest that the number of measures selected depends on the best mix that maximises economic benefits. For instance, there are more measures selected with 60% of the budget compared to those with 80% of the budget and most importantly the increase in capital measures (Table 10-8). This is where the present study demonstrates the ability of the newly developed approach to integrate these two categories of measures. In developing countries, safety improvement programmes are seldom and thus any road safety funds for infrastructure improvement should guarantee benefits in the future and enhance the entire road network safety. These findings clearly demonstrate that the proposed life span approach can guarantee the network safety requirements in developing countries.

Generally, the results show that life span optimisation results in efficient allocation of resources and is superior to the non-life span optimisation due to an improved mix of measures selected for implementation. It appears there are no significant changes in economic benefits in either approach, but life span-based optimisation is tentatively preferred due to economic sustainability of assumed benefits resulting from increased selection of capital measures. Economic sustainability is achieved by reducing the short-term and increasing the long-term economic benefits. The efficient use of the available resources for road safety infrastructure programmes through the application of a life span approach supports economic growth.

As may be seen from this case study, it is evident most developing countries may require more of capital than maintenance countermeasures. Unfortunately, with the non-life span approach, there are more maintenance measures selected than capital measures in all budget scenarios (Table 10-7). This is the most interesting finding of this research; where a life span approach has demonstrated the ability to integrate road safety countermeasures. This new technique presented in this developed model provides efficient allocation of resources for infrastructure measures more especially for road networks requiring major modifications and improvements to improve road safety. Consequently, without life span optimisation, there would be more maintenance countermeasures selected than capital countermeasures. This becomes more evident, as less money is available for implementing infrastructure measures (Table 10-7). The reduction in maintenance measures selected in life span optimisation in comparison to those for non-life span may indicate this as well.

10.6.3 A comparison between Netherlands and Indonesia case studies

The two case studies are quite distinct in terms of budget requirements for capital and maintenance measures.

In Indonesia, capital measures require 85% of the total road safety budget compared to 74% in the Netherlands in the unconstrained scenario. This may suggest that the road network in Indonesia requires a more capital-intensive investment to improve the road safety situation than in the Netherlands. Figure 10.7 shows that the economic benefits due to capital measures are higher in Indonesia than in the Netherlands. This may further indicate the need for capital measures in Indonesia than in the Netherlands to improve the road safety condition. Again, this may be seen with the allocation of 62% and 39% to capital countermeasures in Indonesia and Netherlands respectively with the 25% budget scenario. In fact, the Indonesia case study demonstrates the need for capital countermeasures in most developing countries. However, there appears a big challenge in most developing countries where resource allocation for safety projects is very low despite the enormous need for capital-intensive investments.

This research attempts to offer an innovative solution to this problem by emphasizing the need to consider life span of countermeasures to achieve effectiveness during prioritisation process. Non-life span-based optimisation results show a biased selection in favour of maintenance than capital countermeasures in all budget scenarios. The results from this research provide supporting evidence to adopt the newly developed approach of prioritising measures. Firstly, road safety related capital works programmes may be particularly important and needed when there is need to make major road network improvements to enhance the safety condition. Secondary, since most developing countries struggle with road maintenance programmes due to limited funds, there may be no guarantee of the assumed economic benefits for maintenance measures.

Arguably, these results provide support for the need to consider the life span of measures during prioritisation and selection of measures. Similarly, Figure 10.8 shows that the economic benefits due to maintenance measures are higher in the

Netherlands than in Indonesia. These results appear to suggest a higher need for maintenance countermeasures in the Netherlands than in Indonesia. This may equally be observed with the allocation of 61% and 38% to maintenance countermeasures in Netherlands and Indonesia respectively with the 25% budget scenario. Furthermore, this suggests that road safety related maintenance works programmes are equally important most especially in developed countries. These results may provide evidence that the higher the budget constraints, the higher the importance of maintenance measures (Figure 10.5 and Figure 10.8).

A comparison of these results suggests the importance of all categories of measures and thus the relevance of this newly developed approach in both developed and developing countries. Therefore, in line with the previous study by Sabey (1980), these results support the need for a balance between capital and maintenance countermeasures in order to reduce road traffic accidents in an infrastructure improvement programme. Apparently, this research provides the first attempt in this direction, as there has been relatively little research into effectiveness of road safety programmes.

While there have been a number of strategies to improve the global road safety situation, this research presents this unique strategy for improving the performance of road infrastructure through enhanced road infrastructure safety programmes in developing and developed countries. This comparison leads us to one of the most important findings of this research regarding the differences in road network safety requirements between developed and developing countries.

In general, therefore, it seems that capital and maintenance countermeasures are more important in developing and developed countries respectively under budget constraints. Clearly, the results show the above more especially with the 25% budget scenario. Arguably, based on this, the model demonstrates its suitability and justification in its application to both case studies irrespective of their different road network safety requirements. These findings provide further support for the hypothesis that capital and maintenance countermeasures are incomparable and thus should be distinguished during the prioritisation process.

The results further show a higher number of total crash savings in the unconstrained scenario for Indonesia (55,962 traffic crashes) compared to the Netherlands (29,960 traffic crashes). This clearly shows that crash rates are generally high in developing countries compared to developed countries given implementation of these countermeasures on the 172km and 332km of assessed road networks in Indonesia and Netherlands respectively. Crash reduction due to funds availability is generally similar in both case studies although it is higher in Indonesia than in the Netherlands for the same budget scenarios (Figure 10.6). Despite this, the programme in the Netherlands is more cost effective than that in Indonesia probably due to incomparable unit cost of crashes.

The other important finding in this research is that the number of maintenance measures selected is higher than that for capital measures in all budget scenarios with non-life span optimisation (Table 10-2 and Table 10-7). This applies to both case studies and may thus be used to justify the application of the newly developed model. One possible explanation for this biased selection is the highly cost-effective maintenance measures. Therefore, these findings may help to understand that life span optimisation improves the prioritisation and selection by ensuring a mix between capital and maintenance measures. Unlike in the Netherlands, there are small changes in the number of measures selected in Indonesia case study possibly due to a limitation by the number of capital measures. Consequently, there are minimal changes in resource allocation between capital and maintenance measures in Indonesia compared to the significant changes in Netherlands in all the budget scenarios.

In both cases, the allocation of resources decreases and increases in capital (Figure 10.4) and maintenance measures (Figure 10.5) respectively with increasing budget constraints. The other key interesting finding with the results is the similarity in the selection of more countermeasures with 60% of the budget compared to 80% of the budget. An implication and explanation for this finding is the possibility that selection of countermeasures depends on the best mix that maximises economic benefits while ensuring effective utilisation of the available resources.

Finally, another important finding in this research is the significant change in economic benefits due to these two categories of measures with 60% of the budget. According to these findings, we can infer that this approach may determine the minimum budget required to maximise economic benefits from either capital or maintenance measures. As an example, 60% of the budget is required in both case studies to maximise the economic safety budgets from the implementation of maintenance countermeasures under financial constraints.

10.6.4 Sensitivity analysis

Sensitivity analysis results show that the model is very sensitive to changes in crash severity levels. Proportionate exclusion and inclusion of severity levels such as slight injury and PDO crashes does not affect prioritisation of countermeasures but results in commensurate changes in economic benefits.

To compute fully the economic safety benefits, all possible crash severity levels are required. However, there is limited availability of crash severity data and unit costs in most developing countries, and this might limit possible computation of all economic benefits. However, this newly developed model has demonstrated the possibility of prioritising measures with limited data on crash severity levels. The economic benefits are high for the highest number of severity levels and vice versa. Therefore, optimisation conducted considering fewer crash severity levels results in unrealistic economic safety benefits.

The results show significant changes in computation of economic benefits due to changes in crash severity levels in Indonesia than Netherlands. A possible explanation for this is the higher percentage of the crash unit costs as a percentage of the total cost of all severity levels in Indonesia than in the Netherlands. Generally, the number of measures selected for implementation does not change with changes in crash severity levels in all budget scenarios.

It is also surprising to note that fatal and all injury crash severity levels account for over 80% to the economic benefits in the Netherlands compared to 45% in Indonesia. Similarly, fatal and serious injury crashes contribute over 60% to the economic benefits in the Netherlands compared to 30% in Indonesia. There are, however, possible explanations but key among them is the difference in data quality between the two countries. This generally shows the relative importance of reliable and good quality data in computing economic benefits.

10.7 Summary

The results show that the proposed approach changes both the prioritisation and the number of countermeasures selected for implementation. As an example, the results show that the proposed approach improves the mix between the two categories of countermeasures considered. The balance between capital and maintenance measures changes significantly in terms of resource allocation and prioritisation. For the two case studies considered, below 80% of the budget, the allocation of resources to capital and maintenance measures changes significantly. The allocation of resources to capital and maintenance measures decreases and increases respectively with increasing budget constraints. The economic benefits due to capital measures are high in Indonesia compared to those in the Netherlands. Similarly, the economic benefits due to maintenance measures is high in the Netherlands compared to the benefits in Indonesia.

The findings of this research have further demonstrated that a life span budget optimisation approach is superior to a non-life span approach. Non-life span optimisation results show a biased selection in favour of maintenance measures in all budget scenarios. The findings demonstrate that capital and maintenance measures are equally important, and their importance increases with increasing budget constraints. A comparison of results between the case studies may suggest that capital measures are more important than maintenance measures in Indonesia. Similarly, maintenance measures are more important than capital measures in the Netherlands. Consequently, the economic safety benefits due to capital and maintenance measures are high in Indonesia and Netherlands respectively. The differences in safety condition between these countries may account for the modifications and requirements of their road networks in terms of these two categories of countermeasures.

Generally, capital and maintenance measures should be considered in the context of developing and developed countries. The findings provide further support for the hypothesis that capital and maintenance measures should be distinguished during the prioritisation process. Accordingly, it may be inferred that this new approach may determine the minimum budget required to maximise economic benefits from either capital or maintenance measures.

Sensitivity analysis results have shown that the model is very sensitive to changes in crash severity levels. However, proportionate exclusion and inclusion of severity levels such as slight injury and PDO crashes does not affect the prioritisation of countermeasures but results in commensurate changes in economic benefits.

The next Chapter presents the conclusions and recommendations based on the above discussion of results.

CHAPTER 11: CONCLUSIONS AND RECOMMENDATIONS

11.1 Introduction

To improve the economic models of road safety, this research conducted a systematic literature review of the available road safety investment appraisal models to establish the current knowledge and its gaps. The results from this review led to a comparative study between crash and casualty economic analysis approaches of road safety infrastructure countermeasures. Consequently, its results informed the development of a budget optimisation model with regard to the most effective approach to determine economic safety benefits of infrastructure countermeasures. This Chapter draws the conclusions, recommendations, limitations and suggestions for further work based on the above developments.

11.2 Conclusions

11.2.1 Systematic literature review

(1) There has been a growing attempt in the last ten years to develop road safety investment appraisal models. The main approaches used worldwide, and their associated principles are:

a. SafetyAnalyst, BCA, E^3 and iRAP are the most widely used investment appraisal models. SafetyAnalyst and iRAP are comprehensive decision support tools unlike BCA and E^3 models that appear to be economic analysis models.

b. The BCA and E^3 models have limited application because they conduct analysis up to two countermeasures whereas the SafetyAnalyst and iRAP models can analyse multiple countermeasures.
c. The iRAP model is also limited because it takes into account only 2 severity levels (fatal and serious injuries) compared to at least 4 severity levels in BCA, SafetyAnalyst and E^3 models.
d. The BCA model is unique compared to other models where in addition to reduced crashes (safety benefits), indirect benefits of reduced travel delays, VOC and emissions resulting from reduced crashes are considered.
e. iRAP and SafetyAnalyst models apply systemic and crash-based approaches respectively in screening the road network to identify potential site(s) for safety improvement. In determining the base safety condition, crashes or casualties are determined using observed (historical) data, SPFs, Empirical Bayes (EB) approach and other methods.
f. All models compute the direct benefits using CMFs and a multiplicative method for multiple countermeasures is common though it tends to overestimate safety benefits in some studies.

(2) There is nether uniformity nor universally accepted standards to compute crash or casualty unit costs for road traffic accidents and the life cycle performance of road safety countermeasures.

(3) There are no standardised methods for combining life cycle costs of road safety countermeasures during economic appraisal and all approaches identified by this research ignore end of infrastructure life costs.

(4) Cost benefit analysis still receives criticism due to the value attached to human life, considered meaningless and ethically wrong. Despite this, this tool offers complete assessment of all possible objectives of countermeasure implementation (safety, mobility and environment) as compared to cost effectiveness, easily accepted because it does not involve calculation of crash costs.

(5) Human costs appear to be on average 70% while economic costs are 30% of the crash costs based on computations made using economic and human costs data.

(6) Recommended BCA crash unit costs are higher than unit costs in all models. These BCA unit costs appear to be unrealistic.

(7) The methodology employed by iRAP in estimating the unit cost of a serious injury is not sufficiently accurate since serious injury unit costs computed are much higher than serious injury crash unit costs used in the models.

11.2.2 Comparison between crash and casualty economic analysis approaches

Based on the comparative analysis conducted by this study between crash and casualty economic analyses, the following conclusions may be drawn:

(1) The total cost of road crashes is higher than that of casualties as crashes include a distinct PDO severity level not considered in casualties.

(2) Arguably, the iRAP economic analysis approach, which is typically a casualty-based approach, may underestimate the computation of economic benefits and thus consequently may compromise the economic justification and selection of infrastructure countermeasures.

(3) The importance of including slight injuries in a typical casualty-based approach should be reconsidered in developed countries, where slight injuries constitute up to 85% of the total number of casualties and this accounts for over 20% of the total cost of casualties.

(4) A crash-based approach is superior to a casualty-based approach as the latter may underestimate safety benefits; crash unit costs are higher than casualty unit costs and consequently the economic safety benefits computed using a crash-based approach are high compared to those by a casualty-based approach.

(5) The inclusion of PDO crashes in economic analysis of infrastructure measures may be quite substantial primarily in developed countries where PDO crashes constitute up to 90% of the total crashes and this contributes to over 30% of the total cost of crashes.

(6) A crash-based approach results in a wider range of countermeasures selected for implementation due to enhanced economic justification. As a result, this wide selection improves the programme’s effectiveness due to increased complementary treatments.

(7) A crash-based approach does not change the priority of the countermeasures. However, for a given economic criteria such as a BCR threshold value, the

priority and selection in each approach changes due to differences in the computed economic safety benefits.

(8) The key determinants of the changes in computation of economic benefits in either approach are the severity levels and their respective unit costs. However, significant changes may result from unit costs that are a higher percentage of the total cost of all severity levels.

11.2.3 Budget optimisation model

A budget optimisation approach has been developed by this study which addresses prioritisation and budget constraint challenges that are of interest to road agencies and organisations involved in road network safety improvement programmes. The study draws the following conclusions based on the case studies presented.

(1) A life span-based budget optimisation approach is superior to a non-life span approach.

(2) The newly developed model allocates the available resources efficiently between capital and maintenance countermeasures, thus providing an effective prioritisation technique that considers the life span of countermeasures and financial constraints.

(3) Life span-based optimisation changes prioritisation and consequently the number of countermeasures selected for implementation. Equally, the balance between capital and maintenance countermeasures changes significantly with regard to the resources allocated to each countermeasure category and the resulting economic safety benefits.

(4) The current prioritisation methods and approaches for infrastructure countermeasures based on any economic criteria or optimisation technique produce biased results.

(5) Capital and maintenance countermeasures are equally important. Their importance increases with increasing budget constraints. However, the distinction is that capital and maintenance measures are needed more in developing and developed countries respectively.

(6) Capital and maintenance measures are distinct and complementary to each other. Consequently, the prioritisation process should consider both categories since the effectiveness of road safety programmes depends on the mix between capital and maintenance countermeasures.

(7) There is more maintenance than capital countermeasures selected for implementation in non-life span-based optimisation compared to life span-based optimisation. Therefore, prioritisation based on the life span of countermeasures is more effective due to improved balance between capital and maintenance countermeasures.

(8) The newly developed life span-based optimisation technique may compute the minimum budget required to maximise the economic benefits from either capital or maintenance countermeasures under budget constraints.

(9) There are no significant changes in economic benefits due to countermeasure prioritisation and selection in life span based and non-life span optimisation. However, life span-based optimisation might enhance sustainability of assumed economic benefits due to optimal combination between capital and maintenance countermeasures.

(10) The number of countermeasures selected for implementation depends on the best mix that maximises overall economic safety benefits while ensuring effective utilisation of the available resources.

(11) Proportionate exclusion of some severity levels such as slight injury and PDO crashes does not affect the prioritisation and selection of countermeasures. This only results in commensurate changes in the computation of economic benefits.

(12) The newly developed model provides practical application during prioritisation of infrastructure countermeasures in road network safety investment programmes and is relevant to both developed and developing countries.

11.3 Recommendations

The study recommends the following based on the results of the systematic review, the comparison conducted between crash and casualty economic analysis approaches and the developed budget optimisation model.

(1) Countermeasure prioritisation and selection process should take into consideration the life span of countermeasures to improve the effectiveness of road network safety investment programmes.

(2) Safety analysts and economists should adopt a crash-based approach while conducting economic analysis of safety infrastructure measures to improve business cases presented for road network safety investments.

(3) As the terms cost of a crash and cost of a casualty used interchangeably in the scholarly literature, should be clarified and subsequently strictly used.

(4) To date, there is no universally accepted standard for computing crash/casualty unit costs and the distinction between human and economic costs or direct and indirect costs should be made. A methodology that does not consider the above costs components such as the VOSL requires adjustment for economic or direct costs.

(5) There is need to enhance the current approaches used to compute countermeasure costs so as to take into consideration all life cycle costs of countermeasures.

(6) CMFs relate to the number of crashes prevented by countermeasures instead of casualties and therefore they should be used in crash-based economic analysis and not in casualty-based approaches.

(7) In a casualty based economic analysis approach, this research recommends analysts to consider all the severity levels (fatal, serious and slight injuries) during appraisal as in slight injuries may have a significant impact on the computation of economic benefits and the countermeasures selection.

(8) To facilitate international comparison and enhance the economics of road safety, accident data collection must be standardised and streamlined with regard to both the number of crashes and casualties for all severity levels.

(9) Annual computation of costs for multiple countermeasures with unequal service lives may provide a practical solution to standardise methods for combining life cycle costs of multiple countermeasures.

11.4 Limitations of the study

1. The systematic literature review may not have identified all the relevant studies due to limitations in the search strategy; for example, some scholarly literature may not be in English or included in the databases considered.
2. The identified knowledge and its gaps regarding road safety investment appraisal models is based on documentation presented by iRAP, SafetyAnalyst, BCA and E^3 models.
3. The infrastructure programmes used as case studies in this research are developed based on iRAP's methodology. Therefore, the findings in this research might change with infrastructure programmes developed using a different approach.
4. The study utilises crash and casualty unit costs recommended by the European SafetyCube project and those developed by Sugiyanto and Santi (2017). Therefore, the analysis and conclusions made in this research were due to these unit costs and could vary for different unit rates used.
5. Relatedly, this study draws some relationships between the number of crashes and casualties, which are limited to the data from 9 countries (Austria, Estonia, Finland, Germany, Iceland, Ireland, Norway, Slovenia and UK).
6. In the computation of economic benefits of infrastructure countermeasures, all relevant effects on safety, travel time and environment may have a substantial impact on economic appraisal. In this model development, only the safety economic benefits were included in the model.

7. It appears no previous road safety research has categorised countermeasures using the life-span approach. This research is limited to the tentative categorisation adopted that might change the results using a different criterion.
8. The newly developed optimisation model, built and solved by LINGO software, utilises a branch-and-bound solution algorithm to find the optimal solution. The results of this research might change for an optimisation software that uses a different optimisation algorithm.
9. Finally, the novel approach appears to be the first attempt to prioritise countermeasures considering their life span in a simplified manner and without taking into account specific life spans of the countermeasures selected.

11.5 Further work

The existing and unresolved debates in the economics of road safety investments particularly on the methods used to compute crash/casualty unit costs, economic safety benefits and countermeasure costs clearly give an indication of the required research effort and further work in the subject. Therefore, in the advancement of the economics of road safety infrastructure investments, based on the work reported in this Thesis, these areas require further research.

(1) Research to develop a methodology that combines all life cycle costs of multiple road safety countermeasures with different service lives is an important issue for future research. It is clear the current approaches used to compute countermeasure costs do not capture all costs and appear challenged by unequal life span of countermeasures. This has resulted in non-uniformity and lack of standardisation in the available approaches.

(2) Computing the effectiveness of infrastructure countermeasures in a casualty based economic analysis approach requires further research and probably the need for developing ‘casualty modification factors’ since CMFs are developed based on crashes and not casualties.

(3) Researchers can also explore on crash prediction for individual severity levels such as serious and minor or slight injury crashes etc. since current SPFs predict for total crashes (TOT) and FI crash severity levels only.

(4) The unit cost of serious injuries and other severity levels as a percentage of the VOSL or a comprehensive fatality unit cost is another area for future research. iRAP, for example, developed a ‘rule of thumb’ to compute the value of a serious injury and suggested it was less robust. The current cost of a serious injury as a percentage of the VOSL varies significantly between 10% and 30% and it appears there are no relationships to date between a comprehensive fatality unit cost and the unit costs for other severity levels.

(5) In an attempt to estimate a comprehensive crash/casualty unit cost, an adjustment to cater for the economic/direct cost component may be required. There is some work done in trying to establish the economic/direct cost as a percentage of total unit cost or human/indirect cost that is inconclusive. These relationships are very useful and required especially in developing countries with limited data on the other cost components.

(6) The estimation of human costs is challenging, and approaches used to date have resulted in incomparable figures. Whereas there is substantive research work in this area, there are still arguments and debates amongst scholars regarding the most appropriate and realistic. A much widely accepted and

realistic method to determine these unit costs is potential work for future researchers.

(7) A further study is required to document the relationships between different crash severity levels to aid computations and estimations in the absence of actual crash severity data. This equally applies to the casualty data and its severity levels.

(8) The impact of indirect benefits from the reduction of crashes (travel time, vehicle operating costs, noise and pollution related) on the computation of economic benefits and countermeasure selection is another important area for future research. These impacts if established may improve the consistency and reliability of decisions when evaluating and ranking countermeasures.

(9) Finally, this study introduced the concept of categorising road safety countermeasures based on their life span and tentatively categorised countermeasures as capital and maintenance. Categorising countermeasures is a newly developed concept and thus in future investigations; it might be possible to use a different categorisation criterion.

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APPENDIX A: PUBLICATIONS

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A budget optimisation model for road safety infrastructure countermeasures

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A budget optimisation model for road safety infrastructure countermeasures

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Additional information is available at the end of the article

Abstract: The requirements and modifications to the road infrastructure to achieve high levels of safety require different countermeasures that are not directly comparable considering their life span. It is felt that the effectiveness of a road safety programme highly depends on the best mix between capital and maintenance work measures. To this end, this article introduces a novel methodology that prioritises countermeasures by considering their effectiveness over their life span together with budget constraints, based on a mixed integer linear programming model with an objective function to maximise their economic safety benefits. To illustrate the application of the proposed model developed using the LINGO software, a case study from the Netherlands, Utrecht provincial roads, was used. The results show that this approach seems to enhance both the prioritisation and the number of countermeasures selected for implementation. Furthermore, the method can compute the minimum budget required to maximise the economic benefits from capital work measures. It may also prioritise road safety-related maintenance work programmes and offer a plan for capital works if funds are below the minimum budget. Consequently, this approach appears to enhance the non-life span approach due to an improved mix between capital and maintenance work programmes for road safety.

Chris Bic Byaruhanga

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Chris Bic Byaruhanga is a Doctoral Researcher in the Department of Civil Engineering, University of Birmingham, UK. He received his MSc (Eng) Transport Planning and Engineering from the University of Leeds, UK, in 2012 and further trained in Infrastructure, Development and Finance from the Transport Studies Unit, University of Oxford, UK, and Road Safety from Delft University of Technology, the Netherlands, in 2018. His areas of interest include road safety, transport infrastructure planning and policy. Harry Evdorides is a Lecturer and a Module Lead for Road Safety in the Department of Civil Engineering, University of Birmingham, UK. He obtained a Diploma in Civil Engineering from the Aristotle University of Thessaloniki, Greece. He joined the Highways Group in 1990 as a research student and thereafter obtained his PhD (Civil Engineering) in 1994. His areas of interest include road safety, highway asset management and engineering.

PUBLIC INTEREST STATEMENT

Infrastructure-related safety improvement programmes are usually capital-intensive, requiring planning and management. The road network consisting of sections and junctions and despite being built to engineering standards will usually require improvements and modifications due to changes mainly in traffic volumes and added safety requirements. Consequently, different countermeasures that may be categorised as capital and maintenance will usually be required to improve the safety standards and deficient sections of the road. Arguably, the effectiveness of a road safety programme highly depends on the best mix between these two categories of countermeasures. However, obtaining the optimal combination between capital and maintenance measures in an infrastructure programme is one of the challenges in determining the effective use of countermeasures. This article introduces and develops a unique concept of grouping countermeasures with regard to their life span as part of the prioritisation procedure.

Subjects: Concrete & Cement; Structural Engineering; Sustainability

Keywords: life span; model; infrastructure countermeasures; road safety; budget optimisation; economic benefits

1. Introduction

Infrastructure-related safety improvement programmes are usually capital-intensive, requiring planning and management. Over its life span, the road network consisting of sections and junctions and despite being built to engineering standards will usually require improvements and modifications due to changes mainly in traffic volumes and added safety requirements. Because of these changes, different countermeasures will usually be required to improve the safety standards and deficient sections of the road. The countermeasures may be categorised as capital work and maintenance work. Arguably, the effectiveness of a road safety programme highly depends on the best mix between these two categories of countermeasures. However, obtaining the optimal combination between capital and maintenance works in an infrastructure programme is one of the challenges in determining the effective use of countermeasures (Elvik, 2014). Clearly, the prioritisation and selection techniques employed by the most advanced road safety management systems, such as the SafetyAnalyst (Harwood et al., 2010) and the International Road Assessment Programme (iRAP) model ([iRAP] International Road Assessment Programme, 2015), do not take into account the varying categories of measures, and therefore, this may produce biased results. Furthermore, road safety budgets are usually not sufficient and always suffer cuts and diversions to handle emergencies and other priorities. This may lead to a need for a prioritisation methodology capable of handling budget constraints. Additionally, by considering the above categorisation of countermeasures, optimal allocation of resources between these two categories is equally necessary. To date, the use of economic analyses tools, such as cost-benefit analysis and cost-effectiveness, may provide important insights to countermeasure ranking and selection but seem to be ineffective in handling budget allocation problems (Persaud & Kazakov, 1994). For example, in a constrained budget, selecting countermeasures based on a descending order of benefit-to-cost ratio (BCR) until the budget is exhausted may not yield sustainable and optimal results (Jiang & Sinha, 1990). While previous budget optimisation models (Melachrinoudis & Kozanidis, 2002; Mishra & Khasnabis, 2012; Saha & Ksaibati, 2016) allocated resources amongst measures, highways, intersections or black spots, none of them addresses this specific problem. Certainly, without categorising measures, it is possible to preclude the selection of several countermeasures that may enhance a programme's effectiveness within the budget constraints. An optimisation technique that considers the lives of countermeasures would also improve the sustainability of their assumed economic benefits. In the scholarly literature (Elvik, 2014; Van Uden & Heijkamp, 1995; Weber & Jahrig, 2010), the road safety countermeasures are categorised as short term, medium term and long term based on their service life but without a proper distinction with regard to the budget heads used to fund the implementation of the countermeasures.

A number of researchers (Mahmud et al., 2014; Tziotis, 2011) tentatively grouped road safety countermeasures as capital (long term) and maintenance (short term). Azmi and Evdorides (2019) demonstrated their implementation under a broader road development programme. Subsequently, this study develops the concept of road safety countermeasure prioritisation by considering an optimisation method that takes into account both their lives and the available funding to implement a road safety infrastructure improvement programme.

2. Literature review

Optimisation techniques have been widely applied in operations research, manufacturing, management, transportation engineering and finance. In road safety, dynamic programming (Brown, 1980), linear programming (Behnood & Pino, 2020; Kar & Datta, 2004; Saha & Ksaibati, 2016) and integer programming (Abdolmanafi & Karamad, 2019; Melachrinoudis & Kozanidis, 2002; Mishra & Khasnabis, 2012) techniques have been applied. Dynamic programming is a technique that solves a complex problem through a sequence of simpler sub-problems. Linear programming technique expresses resource allocation problems mathematically in the form of linear equations and inequalities. Integer programming is an optimization technique in which all the variables are restricted to integers. The trend shows the recent application of linear and integer programming, or both, and more specifically, the use of the faster and advanced branch-and-bound technique. Melachrinoudis and Kozanidis (2002) developed a mixed integer allocation model for discrete (at specific points on the road network) and continuous (over the length of the road) improvements to maximise the reduction in the expected number of accidents. Kar and Datta (2004) used a linear programming technique for allocating resources in the state of Michigan to maximise the benefits of reducing total crashes. Similarly, Behnood and Pino (2020) developed a model to minimise a cost-effectiveness index excluding property damage only (PDO) crashes. An optimisation model by Mishra and Khasnabis (2012) allocated resources to maximise monetary benefits due to saved crashes at urban intersections. Another model developed for the best mix of countermeasures to improve black spots by Saha and Ksaibati (2016) allocated resources by maximising benefits in terms of reduced overall crash frequency but ignored PDO crashes. As seen with all these models, allocation of resources is mainly to selected measures, black spot areas, highways, cities or locations with no consideration of the lives of countermeasures, their funding or an entire road network in a comprehensive and optimised manner.

3. Method and proposed model

In computing the economic benefits, investment appraisal models may consider the reductions in the number of crashes or casualties as the safety benefits due to implementation of countermeasures (Byaruhanga & Evdorides, 2021). However, according to Byaruhanga and Evdorides (2022), in any investment appraisal model, it seems advantageous to consider the number of crashes instead of casualties and more so if PDO crashes are included in the analysis. For this reason, this study uses the number of all crashes together with the crash unit rates to determine the economic benefits instead of using casualty numbers. The optimisation model presented hereinafter seeks to determine the optimal expenditure between capital and maintenance works and to maximise the economic benefits under a constrained budget. Its objective function (*Z*) in Equation 1 maximises the economic safety benefits due to reductions in fatal, serious, slight and PDO crashes. These are the monetised benefits computed at the end of the appraisal period taking into consideration discounting.

$$Z = Max \sum_{i=1}^{N} \sum_{k=1}^{K} \begin{bmatrix} (f_i^c f_c + s_i^c s_c + sl_i^c sl_c + Pdo_i^c pdo_c)X_i + \\ (f_k^m f_c + s_k^m s_c + sl_k^m sl_c + Pdo_k^m pdo_c)X_k \end{bmatrix} \tag{1}$$

where f_i^c, $s_i^c, sl_i^c and Pdo_i^c$ represent fatal, serious injury, slight injury and PDO crash savings, respectively, for capital work measure *i* after project execution. f_c, s_c, sl_c and pdo_c are the crash unit costs for fatal, serious injury, slight injury and PDO crashes, respectively. Similarly, $f_k^m, s_k^c, sl_k^m and Pdo_k^m$ represent fatal, serious injury, slight injury and PDO crash savings respectively for maintenance work measure. The main constraint of the model is the total budget (B) given by:

$$\sum_{i=1}^{N} \sum_{k=1}^{K} \left[(C_i^c)X_i + (C_k^m)X_k \right] \leq B \tag{2}$$

$$N_B^c = N_B^m \tag{3}$$

$$X_i \in \{0, 1\} \tag{4}$$

$$X_k \in \{0, 1\} \tag{5}$$

The second constraint (Equation 3) ensures a mix between measures from the two categories. N_B^c *and* N_B^m are the number of selections made for capital and maintenance work measures, respectively, within the available budget (B). C_i^c *and* C_k^m are the discounted costs for capital work measure *i* and maintenance work measure *k*, respectively. *N and K* represent the total number of capital and maintenance work measures, respectively. $X_i and X_k$ are binary decision variables (1 if selected, otherwise 0).

Nowadays, optimization models can easily be developed using computer software such as Premium Solver Platform (Jiang, 2010), General Algebraic Modelling Systems (GAMS; Calasan et al., 2021) and LINGO (LINDO, 2020). LINGO has a remarkable popularity and is currently one of the most powerful and user-friendly software used since its inception in 1980s. Accordingly, in this study, LINGO software developed by Linear Interactive and Discrete Optimizer (LINDO) systems is utilised to run the developed model.

3.1. Model application

The practical application of the newly developed optimisation model is during the prioritisation step of an entire roadway safety management process. Therefore, any appropriate methodology may be adopted during network screening, diagnosis, countermeasure selection, as well as economic appraisal provided benefits and life cycle costs are established for each countermeasure for the analysis period. The key parameters required to run the model are the countermeasures grouped into two categories with regard to their life span together with their individual life cycle costs and economic safety benefits. To illustrate the application of the proposed model, a case study, part of the 20-year infrastructure improvement programme taken from [iRAP] International Road Assessment Programme (2021) for the Netherlands (Utrecht 2014 Provincial Roads), developed using the European Road Assessment Programme (EuroRAP) and the ViDA software, is used. Provincial roads that contribute 6% of the total Dutch network were among the most unsafe roads, with the risk of a serious accident five times higher in comparison to the national road network (ANWB, 2013). Consequently, in 2012 and 2013, the Royal Dutch Touring Club (ANWB) assessed these roads using EuroRAP methodology to recommend effective road safety improvements to prevent these accidents. The results of the assessment showed that over 65% of Utrecht provincial road network (332 km) had a rating of two stars (unsafe conditions). Therefore, the test data represented realistic and effective countermeasures based on these results to improve the assessed road network to a minimum safety level of three stars (safe condition). iRAP is a casualty-based model that considers only two severity levels (fatalities and serious injuries) that may underestimate economic safety benefits (Byaruhanga & Evdorides, 2022). As a result, a more accurate approach that uses crash numbers instead of casualty numbers and considering four severity levels (fatal, serious injury, slight injury and PDO) is preferred in this work. Consequently, part of the Utrecht infrastructure programme was modified, and countermeasures with life years more and less than 10 years were categorised as capital (C) and maintenance (M) work measures, respectively, as shown in Table 1.

Further analysis of the original data established that a total of € 71 million was required to implement countermeasures to yield economic safety benefits of € 590 million (Table 2). In view of the growing funding limitations of safety budgets, it was then assumed that 80%, 60% or even 25% of the budget was available for the programme that required further optimisation. Based on these data, the newly developed model was then used. The study also carried out sensitivity analyses related to changes in crash severity levels and categorisation of measures.

4. Model results and discussion

Table 3 shows the budget allocation under road safety capital or maintenance works and its benefits under unconstrained (100%) budget availability together with the optimised results under certain assumed budget constraints. The results show that the balance between capital and maintenance work measure changes significantly. For instance, under-unconstrained budget

Table 1. Life years of countermeasures

Countermeasure	Life years	Category	Source of information
Pedestrian footpath	10–20	Capital	[iRAP] International Road Assessment Programme, 2010
Median barrier	10–30	Capital	PIARC, 2021; [iRAP] International Road Assessment Programme, 2010; Grzyl et al., 2017 2017
Roadside barrier	10–30	Capital	[iRAP] International Road Assessment Programme, 2010; Daniels & Papadimitriou, 2017; Daniels et al., 2019; Grzyl et al., 2017
Pedestrian fencing	10–20	Capital	[iRAP] International Road Assessment Programme, 2010
Street lighting	10–20	Capital	[iRAP] International Road Assessment Programme, 2010
Traffic calming	10–20	Capital	[iRAP] International Road Assessment Programme, 2010
Bicycle lanes and tracks	10–25	Capital	Elvik et al., 2009; [iRAP] International Road Assessment Programme, 2010
Reconstruction and rehabilitation of roads	25	Capital	Elvik et al., 2009
Pedestrian crossing (signalised)	10–20	Capital	[iRAP] International Road Assessment Programme, 2010
Sight distance (obstruction removal)	5–10	Maintenance	[iRAP] International Road Assessment Programme, 2010
Shoulder rumble strips	1–5	Maintenance	[iRAP] International Road Assessment Programme, 2010
Refuge island	5–10	Maintenance	[iRAP] International Road Assessment Programme, 2010
Protected turn lane (unsignalised 4 leg)	5–10	Maintenance	[iRAP] International Road Assessment Programme, 2010
Unsignalised crossing	1–5	Maintenance	[iRAP] International Road Assessment Programme, 2010
Central hatching	1–5	Maintenance	[iRAP] International Road Assessment Programme, 2010
Parking improvements	5–10	Maintenance	[iRAP] International Road Assessment Programme, 2010
Centreline rumble strip/ flexi-post	1–5	Maintenance	[iRAP] International Road Assessment Programme, 2010

(Continued)

Table 1. (*Continued*)

Countermeasure	Life years	Category	Source of information
Improve delineation	1–5	Maintenance	[iRAP] International Road Assessment Programme, 2010
Protected turn lane (unsignalised 3 leg)	5–10	Maintenance	[iRAP] International Road Assessment Programme, 2010
Wide centreline	5–10	Maintenance	[iRAP] International Road Assessment Programme, 2010
Delineation and signing (intersection)	1–5	Maintenance	[iRAP] International Road Assessment Programme, 2010
Clear roadside hazards—driver side	5–10	Maintenance	[iRAP] International Road Assessment Programme, 2010
Shoulder sealing passenger side (>1 m)	5–10	Maintenance	[iRAP] International Road Assessment Programme, 2010

conditions, 74% and 26% of the total budget is required for capital and maintenance works, respectively. However, in a constrained budget scenario, the higher the budget constraint, the lower the budget allocation for capital works, and, as a consequence, the higher the budget allocation for maintenance works. For example, with 25% of the budget available, the model allocates approximately 40% and 60% to capital and maintenance work measures, respectively. As may be seen, the resulting economic benefits are higher with maintenance than capital work measures (Table 3).

The analysis shows that it is possible to identify a budget level below which maintenance countermeasures have a higher contribution to the overall benefits than the capital works in constrained budget scenarios. For example, the economic benefits in capital investment are higher than maintenance investment for funds above 60% of the budget (Figure 1).

Correspondingly, for funding availability below 60% of the budget, the economic benefits due to capital work measures diminish in comparison to maintenance works. This seems to be consistent with the budget allocation strategy for Greece in 2005 where short-term interventions had the largest share of the safe budgets (Yannis et al., 2008). Table 4 shows countermeasures prioritised during the optimisation process for different budget scenarios using the newly developed model. These were selected from the programme of countermeasures (Table 2) that are ideally identified to improve the safety condition of the road network during the road network safety management process. As may be observed, fewer countermeasures are selected and prioritised in comparison to those in Table 2 due to budget constraints usually faced by road safety improvement programmes. Furthermore, the results in Table 4 show that the number of countermeasures selected for implementation is dependent on the best mix that maximises economic benefits for any funds available. As an example, the model selected 22 countermeasures with 80% of the budget in comparison to 24 countermeasures for the 60% availability (Table 4). The model outputs seem to be reasonable for this case study, as revealed by the 16 countermeasures (Table 4) selected with 25% availability that produce the lowest cost-effectiveness ratio.

A non-life span approach showed that prioritisation changes in which there were more maintenance work measures selected than capital work for all budget scenarios in comparison to the life span approach resulted in Table 4. This clearly indicates the possibility of a biased selection in

Table 2. A programme of countermeasures in unconstrained budget

S/N	Countermeasure	Category	Length/ sites	Crashes minimised				Economic benefits (€)	Costs(€)	BCR
				Fatal	Serious injury	Slight injury	PDO			
1	Signalised crossing	C	1 sites	1.2	7.7	41.9	397.5	88,29,598	45,000	196
2	Pedestrian fencing	C	27.20 km	1.0	6.9	37.7	357.8	79,46,638	1,79,606	44
3	Street lighting (intersection)	C	14 sites	2.4	16.1	88.0	834.8	1,85,42,156	5,04,000	37
4	Traffic calming	C	2.90 km	0.1	0.8	4.2	39.8	8,82,960	87,581	10
5	Central median barrier (no duplication)	C	0.70 km	0.1	0.8	4.2	39.8	8,82,960	95,182	9
6	Footpath provision driver side (>3 m from road)	C	25.40 km	3.3	21.5	117.4	1113.1	2,47,22,875	29,22,040	8
7	Footpath provision passenger side (>3 m from road)	C	26.80 km	3.4	22.3	121.6	1152.9	2,56,05,835	30,85,368	8
8	Footpath provision driver side (informal path >1 m)	C	4.70 km	0.1	0.8	4.2	39.8	8,82,960	1,14,747	8
9	Footpath provision driver side (adjacent to road)	C	27.90 km	4.1	26.9	146.7	1391.4	3,09,03,593	43,88,280	7
10	Bicycle Lane (off-road)	C	3.50 km	0.3	2.3	12.6	119.3	26,48,879	3,92,156	7
11	Footpath provision passenger side (adjacent to road)	C	44.10 km	6.0	39.9	218.0	2067.2	4,59,13,910	69,39,120	7
12	Roadside barriers—driver side	C	206.20 km	23.1	152.9	834.1	7911.1	17,57,09,003	2,78,98,500	6
13	Footpath provision passenger side (informal path >1 m)	C	5.80 km	0.1	0.8	4.2	39.8	8,82,960	1,41,451	6
14	Central median barrier (1 + 1)	C	34.80 km	4.8	31.5	171.9	1629.9	3,62,01,352	62,88,200	6
15	Road surface rehabilitation	C	0.80 km	0.0	0.3	1.7	15.9	3,53,184	70,435	5
16	Improve curve delineation	M	0.40 km	0.1	0.4	2.1	19.9	4,41,480	7,460	59
17	Sight distance (obstruction removal)	M	1.40 km	0.2	1.5	8.4	79.5	17,65,920	35,280	50
18	Shoulder rumble strips	M	199.30 km	9.8	64.5	352.1	3339.4	7,41,68,624	23,82,592	31
19	Refuge Island	M	14 sites	1.6	10.8	58.7	556.6	1,23,61,437	4,16,422	30
20	Protected turn lane (unsignalised 4 leg)	M	3 sites	1.6	10.8	58.7	556.6	1,23,61,437	5,35,399	23
21	Unsignalised crossing	M	5 sites	0.5	3.1	16.8	159.0	35,31,839	2,17,465	16
22	Central hatching	M	5.70 km	0.1	0.5	2.5	23.9	5,29,776	34,173	16

(*Continued*)

Table 2. (*Continued*)

S/N	Countermeasure	Category	Length/ sites	Crashes minimised				Economic benefits (€)	Costs(€)	BCR
				Fatal	Serious injury	Slight injury	PDO			
23	Parking improvements	M	1.50 km	0.0	0.2	1.3	11.9	2,64,888	18,900	14
24	Centreline rumble strip/flexi-post	M	1.80 km	0.0	0.2	1.3	11.9	2,64,888	19,512	14
25	Improve Delineation	M	45.70 km	1.5	10.0	54.5	516.8	1,14,78,478	8,47,446	14
26	Protected turn lane (unsignalised 3 leg)	M	54 sites	8.6	56.9	310.2	2941.8	6,53,39,026	72,10,571	9
27	Wide centreline	M	12.50 km	0.1	0.5	2.5	23.9	5,29,776	75,710	7
28	Delineation and signing (intersection)	M	8 sites	0.1	0.4	2.1	19.9	4,41,480	88,582	5
29	Clear roadside hazards—driver side	M	0.10 km	0.0	0.1	0.4	4.0	88,296	20,000	4
30	Shoulder sealing passenger side (>1 m)	M	71.50 km	3.4	22.3	121.6	1152.9	2,56,05,835	63,34,720	4
	Total			**78**	**513**	**2,801**	**26,568**	**59,00,82,044**	**7,13,95,898**	

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Table 3. Budget optimisation results

Unconstrained budget (100%)	**Category**	**Budget (€)**	**Economic benefits (€)**	**Budget (%)**	**Economic benefits (%)**
	Capital	5,31,51,666	38,09,08,864	74%	65%
	Maintenance	1,82,44,232	20,91,73,180	26%	35%
	Total	**7,13,95,898**	**59,00,82,044**	**29,960 (100%)**	
Constrained budget (optimisation results)					
A. 80% (€57,116,718)	Capital	4,62,15,112	34,02,92,712	81%	67%
	Maintenance	1,08,97,774	17,11,17,612	19%	33%
	Total	**5,71,12,886**	**51,14,10,324**	**25,966 (87%)**	
0	0	0	0	0	0
B. 60% (€42,837,539)	Capital	2,47,19,559	20,16,68,022	58%	49%
	Maintenance	1,81,16,138	20,83,78,516	42%	51%
	Total	**4,28,35,697**	**41,00,46,538**	**20,819 (69%)**	
0	0	0	0	0	0
C. 25% (€17,848,975)	Capital	69,89,212	8,77,66,206	39%	34%
	Maintenance	1,08,39,362	17,04,99,540	61%	66%
	Total	**1,78,28,574**	**25,82,65,746**	**13,113 (44%)**	

the absence of life span categorisation. The major disadvantage with such a biased selection is the preclusion of certain measures that might improve the programme effectiveness most especially with limited funding of the safety budget. Arguably, with the life span-based approach, there is more guarantee and sustainability of the assumed economic safety benefits due to an improved mix between the two categories.

It seems therefore that this model may provide a solution to an earlier challenge identified by Elvik (2014) of obtaining the best mix between these two categories of countermeasures, more so in a financial constraint. Generally, maintenance-related measures in this case study are more cost-effective than capital work measures in all budget scenarios. Indeed, this life span-based approach improves the integration between the two different categories of measures. Sensitivity results show

Figure 1. Economic benefits at different budget availability levels.

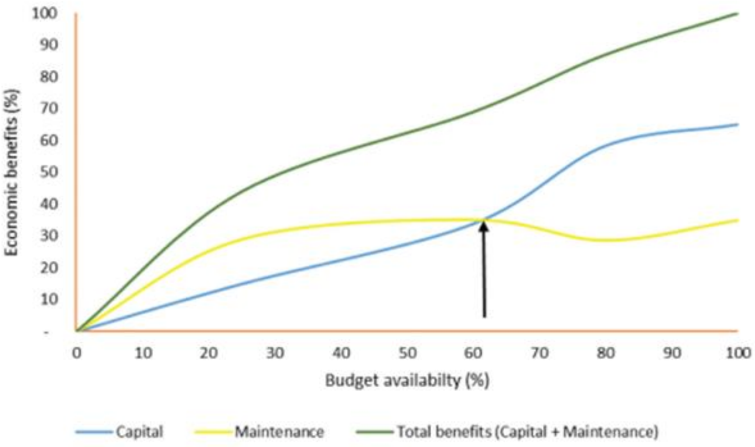

Table 4. Countermeasure selection for different budget scenarios

A: 80% Budget availability

S/N	Countermeasure	Category	Length/ sites	Crashes minimised				Economic benefits (€)	Costs(€)	BCR
				Fatal	Serious injury	Slight injury	PDO			
1	Signalised crossing	C	1 sites	1.2	7.7	41.9	397.5	88,29,598	45,000	196
2	Pedestrian fencing	C	27.20 km	1.0	6.9	37.7	357.8	79,46,638	1,79,606	44
3	Street lighting (intersection)	C	14 sites	2.4	16.1	88.0	834.8	1,85,42,156	5,04,000	37
4	Traffic calming	C	2.90 km	0.1	0.8	4.2	39.8	8,82,960	87,581	10
5	Central median barrier (no duplication)	C	0.70 km	0.1	0.8	4.2	39.8	8,82,960	95,182	9
6	Footpath provision driver side (>3 m from road)	C	25.40 km	3.3	21.5	117.4	1113.1	2,47,22,875	29,22,040	8
7	Footpath provision passenger side (>3 m from road)	C	26.80 km	3.4	22.3	121.6	1152.9	2,56,05,835	30,85,368	8
8	Footpath provision driver side (adjacent to road)	C	27.90 km	4.1	26.9	146.7	1391.4	3,09,03,593	43,88,280	7
9	Footpath provision passenger side (adjacent to road)	C	44.10 km	6.0	39.9	218.0	2067.2	4,59,13,910	69,39,120	7
10	Roadside barriers—driver side	C	206.20 km	23.1	152.9	834.1	7911.1	17,57,09,003	2,78,98,500	6
11	Road surface rehabilitation	C	0.80 km	0.0	0.3	1.7	15.9	3,53,184	70,435	5
12	Improve curve delineation	M	0.40 km	0.1	0.4	2.1	19.9	4,41,480	7,460	59
13	Sight distance (obstruction removal)	M	1.40 km	0.2	1.5	8.4	79.5	17,65,920	35,280	50
14	Shoulder rumble strips	M	199.30 km	9.8	64.5	352.1	3339.4	7,41,68,624	23,82,592	31
15	Refuge Island	M	14 sites	1.6	10.8	58.7	556.6	1,23,61,437	4,16,422	30
16	Protected turn lane (unsignalised 4 leg)	M	3 sites	1.6	10.8	58.7	556.6	1,23,61,437	5,35,399	23
17	Unsignalised crossing	M	5 sites	0.5	3.1	16.8	159.0	35,31,839	2,17,465	16
18	Central hatching	M	5.70 km	0.1	0.5	2.5	23.9	5,29,776	34,173	16
19	Parking improvements	M	1.50 km	0.0	0.2	1.3	11.9	2,64,888	18,900	14
20	Centreline rumble strip/flexi-post	M	1.80 km	0.0	0.2	1.3	11.9	2,64,888	19,512	14
21	Protected turn lane (unsignalised 3 leg)	M	54 sites	8.6	56.9	310.2	2941.8	6,53,39,026	72,10,571	9
22	Clear roadside hazards—driver side	M	0.10 km	0.0	0.1	0.4	4.0	88,296	20,000	4
	Total			**67**	**445**	**2,428**	**23,026**	**51,14,10,324**	**5,71,12,886**	

(Continued)

Table 4. (*Continued*)

B: 60% Budget availability										
1	Signalised crossing	C	1 sites	1.2	7.7	41.9	397.5	88,29,598	45,000	196
2	Pedestrian fencing	C	27.20 km	1.0	6.9	37.7	357.8	79,46,638	1,79,606	44
3	Street lighting (intersection)	C	14 sites	2.4	16.1	88.0	834.8	1,85,42,156	5,04,000	37
4	Traffic calming	C	2.90 km	0.1	0.8	4.2	39.8	8,82,960	87,581	10
5	Central median barrier (no duplication)	C	0.70 km	0.1	0.8	4.2	39.8	8,82,960	95,182	9
6	Footpath provision driver side (>3 m from road)	C	25.40 km	3.3	21.5	117.4	1113.1	2,47,22,875	29,22,040	8
7	Footpath provision passenger side (>3 m from road)	C	26.80 km	3.4	22.3	121.6	1152.9	2,56,05,835	30,85,368	8
8	Footpath provision driver side (informal path >1 m)	C	4.70 km	0.1	0.8	4.2	39.8	8,82,960	1,14,747	8
9	Footpath provision driver side (adjacent to road)	C	27.90 km	4.1	26.9	146.7	1391.4	3,09,03,593	43,88,280	7
10	Footpath provision passenger side (adjacent to road)	C	44.10 km	6.0	39.9	218.0	2067.2	4,59,13,910	69,39,120	7
11	Central median barrier (1 + 1)	C	34.80 km	4.8	31.5	171.9	1629.9	3,62,01,352	62,88,200	6
12	Road surface rehabilitation	C	0.80 km	0.0	0.3	1.7	15.9	3,53,184	70,435	5
13	Improve curve delineation	M	0.40 km	0.1	0.4	2.1	19.9	4,41,480	7,460	59
14	Sight distance (obstruction removal)	M	1.40 km	0.2	1.5	8.4	79.5	17,65,920	35,280	50
15	Shoulder rumble strips	M	199.30 km	9.8	64.5	352.1	3339.4	7,41,68,624	23,82,592	31
16	Refuge Island	M	14 sites	1.6	10.8	58.7	556.6	1,23,61,437	4,16,422	30
17	Protected turn lane (unsignalised 4 leg)	M	3 sites	1.6	10.8	58.7	556.6	1,23,61,437	5,35,399	23
18	Unsignalised crossing	M	5 sites	0.5	3.1	16.8	159.0	35,31,839	2,17,465	16
19	Central hatching	M	5.70 km	0.1	0.5	2.5	23.9	5,29,776	34,173	16
20	Parking improvements	M	1.50 km	0.0	0.2	1.3	11.9	2,64,888	18,900	14
21	Improve Delineation	M	45.70 km	1.5	10.0	54.5	516.8	1,14,78,478	8,47,446	14
22	Protected turn lane (unsignalised 3 leg)	M	54 sites	8.6	56.9	310.2	2941.8	6,53,39,026	72,10,571	9
23	Wide centreline	M	12.50 km	0.1	0.5	2.5	23.9	5,29,776	75,710	7
24	Shoulder sealing passenger side (>1 m)	M	71.50 km	3.4	22.3	121.6	1152.9	2,56,05,835	63,34,720	4
	Total			**54**	**357**	**1,947**	**18,462**	**41,00,46,538**	**4,28,35,697**	

(*Continued*)

Table 4. (*Continued*)

C: 25% Budget availability										
1	Signalised crossing	C	1 sites	1.2	7.7	41.9	397.5	88,29,598	45,000	196
2	Pedestrian fencing	C	27.20 km	1.0	6.9	37.7	357.8	79,46,638	1,79,606	44
3	Street lighting (intersection)	C	14 sites	2.4	16.1	88.0	834.8	1,85,42,156	5,04,000	37
4	Traffic calming	C	2.90 km	0.1	0.8	4.2	39.8	8,82,960	87,581	10
5	Central median barrier (no duplication)	C	0.70 km	0.1	0.8	4.2	39.8	8,82,960	95,182	9
6	Footpath provision driver side (>3 m from road)	C	25.40 km	3.3	21.5	117.4	1113.1	2,47,22,875	29,22,040	8
7	Footpath provision passenger side (>3 m from road)	C	26.80 km	3.4	22.3	121.6	1152.9	2,56,05,835	30,85,368	8
8	Road surface rehabilitation	C	0.80 km	0.0	0.3	1.7	15.9	3,53,184	70,435	5
9	Improve curve delineation	M	0.40 km	0.1	0.4	2.1	19.9	4,41,480	7,460	59
10	Sight distance (obstruction removal)	M	1.40 km	0.2	1.5	8.4	79.5	17,65,920	35,280	50
11	Shoulder rumble strips	M	199.30 km	9.8	64.5	352.1	3339.4	7,41,68,624	23,82,592	31
12	Refuge Island	M	14 sites	1.6	10.8	58.7	556.6	1,23,61,437	4,16,422	30
13	Protected turn lane (unsignalised 4 leg)	M	3 sites	1.6	10.8	58.7	556.6	1,23,61,437	5,35,399	23
14	Unsignalised crossing	M	5 sites	0.5	3.1	16.8	159.0	35,31,839	2,17,465	16
15	Central hatching	M	5.70 km	0.1	0.5	2.5	23.9	5,29,776	34,173	16
16	Protected turn lane (unsignalised 3 leg)	M	54 sites	8.6	56.9	310.2	2941.8	6,53,39,026	72,10,571	9
	Total			**34**	**225**	**1,226**	**11,628**	**25,82,65,746**	**1,78,28,574**	

that proportionate exclusion and inclusion of severity levels, such as slight injury and PDO crashes, do not affect prioritisation of countermeasures but result in commensurate changes in economic benefits.

5. Conclusion

This article presents an optimal budget allocation method addressing prioritisation of infrastructure countermeasures for road safety programmes under budget constraints by considering the life span of the countermeasures and their categorisation as capital or maintenance work. The conclusions that may be drawn, based on the case study presented, are as follows:

(1) The importance of road safety-related maintenance programmes is high. The higher the budget constraints, the higher its importance.

(2) The consideration of the life span of road safety countermeasures changes both their selection and prioritisation for subsequent implementation. It also increases the overall effectiveness of a road safety investment plan.

(3) Using a formal optimisation method, it is possible to define a threshold level of investment above which the impact of capital countermeasures is superior to that of maintenance.

(4) The economic benefits due to prioritised and selected countermeasures are commensurate with changes in the crash severity levels.

(5) Proportionate exclusion of some severity levels, such as slight injury and PDO crashes, does not affect the prioritisation and selection of countermeasures.

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A COMPARISON BETWEEN CRASH AND CASUALTY ECONOMIC ANALYSIS APPROACHES OF ROAD SAFETY INFRASTRUCTURE COUNTERMEASURES

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Abstract: The economic analysis of safety measures is one of the core elements of a road safety program aimed at determining accurately the economic benefits. However, there is still a mix of approaches in some of the most widely used road safety investment appraisal models. For example, SafetyAnalyst is a crash-based evaluation model while the International Road Assessment Programme (iRAP) is a casualty-based model. The objective of this study was to compare crash with casualty based economic analysis approaches of infrastructure related safety countermeasures to inform economists and road safety analysts on the most appropriate approach. The study utilises data from 9 countries and the 20-year infrastructure improvement program for Netherlands developed using EuroRAP and ViDA software. The results of this study demonstrated that a crash-based approach is more comprehensive and results in a wider range of countermeasures selected for implementation. In addition, compared to a casualty-based approach the value of safety benefits and the number of countermeasures selected increased by 26% and 10% respectively using a crash-based approach. This paper suggests that any road safety appraisal model may perform better by considering crashes instead of casualties and more so if the property damage only crashes are included in the analysis.

Keywords: road safety, economic analysis, infrastructure countermeasures, crash unit cost, casualty unit cost, model.

1. Introduction

The economic analysis of road safety countermeasures is one of the core elements of a road safety program aimed at determining accurately the economic benefits (Welle *et al.*, 2018). However, as evidenced in the most widely used road safety investment appraisal models, SafetyAnalyst (Harwood *et al.*, 2010) and Benefit Cost Analysis (BCA) by FHWA (2018) are crash-based models while the International Road Assessment Programme (iRAP, 2015) is a casualty-based model. Moreover, Economic Efficiency Evaluation (E^3) model conducts economic analysis for both crashes and casualties (Martensen and Lassare, 2017); in this case, the choice depends on whether the countermeasure is to prevent crashes thus using a crash-based approach or mitigating the consequences of a crash such as seatbelts thus using a casualty-based approach. To this end, the focus of this paper is to examine the selection of infrastructure measures

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to prevent crashes versus a casualty-based approach that may underestimate benefits within a comprehensive safe road system.

Harmon *et al*. (2018) recommends analysts to work with crashes and crash unit costs during economic appraisal of safety countermeasures. Similarly, in a report by OECD/ITF (2015), the efficiency assessment of a safety related measure requires the number of road crashes or accidents affected by a measure. In PIARC (2020), the key measure to assess effectiveness of any safety infrastructure intervention is the expected reduction in crashes expressed as a crash modification factor (CMF). However, Martensen *et al*. (2016) considers the effectiveness of a measure as a reduction in either the number of crashes or the number of casualties. Similarly, the most common ways of measuring progress in road safety is by the number of road crashes, the number of road casualties and the associated negative consequences (Wegman, 2017). In practice, crash and casualty-based approaches are used in economic analysis of road safety infrastructure measures most probably without due consideration of the impact of either approach on the calculated economic benefits and ultimately the selection of countermeasures. The economic implications might be substantial if for instance instead of analysing crashes, casualties are analysed and a significant proportion of crashes not involving casualties are not considered. For instance, in Germany and Finland, the property damage only (PDO) crashes have a share of up to 50% in total costs for road crashes. Furthermore, in the analysis conducted for countries that include all severity levels, PDO crashes accounted for 2% to 55% share in the total cost of crashes, which is higher than that of slight injuries ranging between 1.9% and 34% (Wijnen *et al*., 2017). Therefore, this study aims to clarify the economic benefits of these two approaches and their impact in the selection of infrastructure countermeasures.

1.1. Economic Analysis of Road Safety Countermeasures

Economic analysis is a process that allows organisations to identify, quantify and determine the value of economic costs and benefits of chosen countermeasures over the appraisal period to ensure efficiency and effectiveness of safety programs (U.S. DOT, 2003). Cost effectiveness, cost utility and cost benefit analyses tools identify how to use scarce resources to obtain the greatest possible benefit or the highest return on investments in road safety (Martensen *et al*., 2018).

The concept of economic analysis for safety measures is quite challenging due to the complex nature of determining the life cycle costs and benefits of countermeasures as well as crash or casualty unit costs. Consequently, this has led to arguments by Hauer (2011) describing the cost benefit analysis (CBA) tool as deficient due to uncertainties in defining the value of statistical life (VOSL) used. However, PIARC (2020) and Safety CaUsation, Benefits and Efficiency (SafetyCube) Decision Support System (Martensen *et al*., 2018) typically accept and use CBA as an economic evaluation tool. There is more substance to this tool subject to parameter estimation enhancement. For instance, this tool can underestimate safety benefits depending on the approach used; thus the need for sound economic analysis. The tool commonly used in road safety research determines the policy priorities and resource allocation typically through safety benefits expressed in terms of reduced number of crashes or casualties.

A crash-based approach refers to an economic analysis in which the safety benefits of implementing a countermeasure are the number of crashes reduced. A road crash or accident refers to unplanned or uncontrolled event involving at least one vehicle, cyclist or motorcyclist and in which at least one person is killed, injured or property is damaged. Therefore, a crash can be fatal (at least one person is killed), serious (at least one person is seriously injured and no person killed), slight (at least one person is slightly injured but no person is killed or seriously injured) and finally a PDO crash in which no person is killed nor injured. In a casualty-based approach, the safety benefits of implementing a countermeasure are the number of casualties reduced. A casualty refers to a person killed or injured in a crash, subdivided into killed, seriously injured and slightly injured. In terms of severity levels, a crash-based approach has more severity levels than a casualty due to the property damage level added that might have a significant effect on the analysis results. In order to perform a CBA all relevant effects of the measure relating to safety, mobility (travel and vehicle expenses) and environment are paramount. However, the effects on mobility and environment appear complex to estimate and are scarce in the scholarly literature. Consequently, most of the appraisal models like SafetyAnalyst and iRAP ignore such effects in their economic analysis except the BCA model that estimates these effects based on reduced number of crashes. Therefore, in the advancement of economic analysis of safety measures, in order to utilise the available research with regard to mobility and environment, it is imperative that analysts develop or modify their models to analyse crash numbers instead of casualties.

2. Methodology and Data

To demonstrate the above approaches, the total cost of crashes and casualties was computed first using the number of crashes/casualties (Table 1) for 9 European countries with the respective European Union (EU) standard crash and casualty unit costs for 2015 (Table 2 and Table 3) for each severity level and adding them together for each country.

Table 1
Crash and Casualty Data

Country	Crashes				Casualties		
	Fatal	Serious Injury	Slight Injury	PDO	Fatalities	Serious Injuries	Slight Injuries
Austria	429	9,262	26,917	646,553	523	10,502	34,522
Estonia	61	433	1,345	29,218	67	467	1,756
Finland	208	475	4,641	478,863	229	519	6,186
Germany	3,187	58,744	240,504	2,104,250	3,377	67,732	321,803
Iceland	16	155	741	5,500	16	178	1,130
Ireland	179	398	4,399	21,734	188	508	6,252
Norway	148	597	4,380	403,719	160	693	5,670
Slovenia	112	868	5,605	11,358	120	932	7,778
UK	1,658	20,676	123,988	2,232,305	1,775	22,807	169,895

Source: (Wijnen et al., 2017)

These unit costs developed by the European SafetyCube project aim to support stakeholders in conducting economic efficiency evaluation of measures. Secondly, the study computed a simple benefit cost ratio (BCR) to demonstrate the effect of these approaches on countermeasure selection considering only countermeasures with a BCR greater than 3. The monetary safety benefits are the number of crashes/casualties reduced multiplied with the respective unit costs (Table 2 and Table 3) and added together for all the severity levels. The 20-year infrastructure improvement program (Table A1) for Netherlands (Utrecht 2014 Provincial Roads) taken from iRAP (2021), developed using EuroRAP and ViDA software is used and modified accordingly to compute BCR.

Table 2

Crash Unit Cost and Components

Severity Level	Medical Costs	Production Loss	Human Costs	Property Damage	Administrative Costs	Other Costs	Total Unit Costs (€)
Fatal	11,757	727,616	1,809,467	17,542	8,891	3,817	2,579,090
Serious Injury	19,158	50,285	263,945	11,143	5,557	709	350,797
Slight injury	1,957	3,629	21,212	7,231	2,677	634	37,340
PDO	0	0	0	2795	764	400	3,959

Source: (Wijnen et al., 2017)

Table 3

Casualty Unit Cost and Components

Severity Level	Medical Costs	Production Loss	Human Costs	Property Damage	Administrative Costs	Other Costs	Total Unit Costs (€)
Fatalities	5,430	655,376	1,587,001	11,555	6,346	3,638	2,269,346
Serious Injuries	16,719	43,627	230,385	7,622	4,364	413	303,130
Slight Injuries	1,439	2,669	15,597	5,317	1,876	519	27,417

Source: (Wijnen et al., 2017)

In iRAP, the number of casualties reduced due to countermeasure implementation depend on the risk factors that change the star rating score for the 100m road segments. This data was the basis in estimating the number of fatalities and injuries and the number of crashes for all severity levels using the ratios (Table 4 and Table 5) developed from real crash and casualty data (Table 1).

Table 4

Relationship between Crash and Casualty Severity Levels

Crash	Casualties		
	Fatalities	Serious Injuries	Slight Injuries
Fatal	1.08	-	-
Serious Injury	-	1.14	-
Slight Injury	-	-	1.35

Source: (Author's own computation)

Table 5
Relationship between Casualty Severity Levels

Casualties		
Fatality	Serious Injuries	Slight Injuries
1	7	45

Source: (Author's own computation)

The ratios in Table 4 are comparable to the number of casualties per crash by severity level in Greece and Norway (Wijnen *et al.*, 2017) and those used in other countries and studies to estimate the number of crashes (De Brabander and Veereck, 2007; Wijnen, 2020). The total number of fatalities and serious injuries (FSI) as per iRAP was split considering 7 serious injuries per fatality (Table 5) which is slightly lower than the 10 serious injuries per fatality used in iRAP (iRAP, 2015). The PDO crashes are 88.7% of the total crashes using data in Table 1 and this determined the number of PDO crashes in the crash-based approach. Therefore, in this study for every injury, there are approximately 6 PDO crashes, which is comparable to the recommended 6 PDO crashes in urban areas and 5.3 PDO crashes established in South Africa (Luathep and Tanaboriboon, 2005).

3. Results and Discussion

The study has compared crash and casualty economic analysis approaches and their impact on countermeasure selection during economic appraisal of safety related infrastructure countermeasures. It is limited to the crash and casualty data, crash-to-casualty ratios, crash/casualty unit costs and the cost of countermeasures presented. In addition, other principles involved in cost estimation such as discounting are not considered.

3.1. Comparing the total cost of crashes and casualties

Table A2 presents the cost of crashes and casualties computed using crash/casualty numbers with their respective unit costs. Considering all the severity levels in both cases, on average, the total cost of crashes is higher by over 70% compared to the total cost of casualties. In countries like Finland and Norway, the total cost of crashes is much higher since 99% of the total crashes are PDO crashes. On average, the PDO crashes are approximately 90% of the total number of crashes and these account for over 30% of the total cost of crashes which agrees with the previous findings by Wijnen *et al.* (2017) where in Germany and Finland the PDO crashes had a share of up to 50% of the total cost of road crashes. Similarly, in a study conducted in Singapore, the PDO crashes were 50% of the total cost of crashes (Chin, 2003). In addition, in Netherlands, about 24% of the total cost of crashes is attributable to PDO crashes (SWOV, 2020). This implies that PDO crashes generally have a significant impact on the total cost of crashes and thus on the results of an economic analysis of countermeasures. Therefore, in an economic appraisal of road safety countermeasures, considering the number of crashes prevented gives a more realistic representation of the actual benefits that might accrue with countermeasure implementation than the casualty approach. In addition, the safety benefits are higher in a crash-based approach as the crash unit cost is usually higher than a casualty unit cost since crashes include one or more vehicles and persons (Wijnen *et al.*, 2017; De Brabander and Vereeck, 2007).

3.2. The Impact of Crash and Casualty Approaches on Countermeasure Selection

Table A3 presents the recomputed BCR values using the iRAP approach, which have changed significantly largely due to the unit costs and ratios used presented in Table 3 and Table 5 respectively that perhaps differ from those used to compute the BCR values in Table A1. The iRAP model performs economic analysis of single or multiple countermeasures during the preparation of the safer roads investment plans (iRAP, 2015). Although iRAP does not consider all the injury severity levels, it is typically a casualty-based model. In this approach, the number of fatalities and serious injuries saved are considered and this results into the selection of 26 countermeasures (Table A3).

Including the number of slight injuries saved in the casualty-based approach results in the selection of 30 countermeasures presented in Table A4. This represents an increase of 15% in the number of countermeasures selected compared to the iRAP approach. In addition, the value of safety benefits increases by 28% for each of the countermeasures in the casualty-based approach. For example, the safety benefits of implementing signalised crossings increase from €5.5 million in the iRAP approach to €7.0 million in the casualty-based approach.

Generally, the change in the number of countermeasures selected and safety benefits is significant because slight injuries on average are 85% of the total number of casualties and account for over 20% of the total cost of casualties (Table A2) which is between 1.9% and 34% previously established by Wijnen *at al.* (2017). In Great Britain (DfT, 2020), the slight injuries were 79% of the total number of casualties in 2019. This gives an implication, that even in a casualty-based model like iRAP, it is important to consider slight injuries during economic appraisal of countermeasures as they have a significant impact on countermeasure selection.

In the crash-based approach, there are 33 countermeasures selected for implementation as presented in Table A5. This accounts for a 10% increase in the number of countermeasures selected compared to the casualty-based approach shown in Table A4. In addition, the safety benefits increase by 26% for each of the countermeasures being analysed. For instance, the safety benefits of implementing signalised crossings increase from €7.0 million in casualty-based approach to €8.8 million in crash-based approach. Generally, the results show that a crash-based approach is more effective compared to a casualty-based approach as the BCR threshold values are increased. This explains why road safety economists should ideally work with crashes and not casualties as previously recommended by Harmon *et al.* (2018). The increase is justified partly by the large number of PDO crashes, which on average are 90% of the total crashes (c.f. Table A2) which is comparable to 88.3% established on the network of Korean expressways in 2008 by Park *et al.* (2012). Therefore, in a casualty-based approach, there is a likelihood of a good number of crashes not considered that may not result in any casualty as seen above.

The difference in unit costs together with the number of PDO crashes have a much higher impact on the economic analysis results. This supports the previous argument by Wijnen *et al.* (2017) where the PDO crashes are major cost components in most countries and their exclusion might result in underestimation of total cost of crashes. This impact is cumulative with more severity levels considered and becomes substantial with the addition of PDO crashes, which are usually more than the other severity levels. The implementation of a particular measure may have differing effects depending on the severity level, which is important in any evaluation. It is important at this stage to remember that most infrastructure measures are designed based on an analysis of crash data and accident causation and not on casualties' causation thus leading to countermeasure effectiveness often expressed in terms of a crash reduction and not a casualty reduction, hence the common term CMF. In addition, to facilitate international comparison and standardise accident data collection, economic analysis of countermeasures must also be standardised and streamlined with regard to the crash-based approach.

The analysis above is a specific case study used as a demonstrator of the need to consider crash-based costs instead of casualty-based costs and without examining whether there are constraints in the road safety budget. In addition, the overall countermeasures prioritisation procedure requires examination with regard to the existing road conditions together with the selection and prioritisation mechanism. For example, it is important to group the countermeasures with regard to their frequency of implementation and the budget source. In other words, distinction is required of the above countermeasures as routine, periodic or rehabilitation works. This can have a significant impact on the final selection of countermeasures together with any budget constraints of the agency responsible for implementing the above countermeasures programme (Azmi and Evdorides, 2019).

4. Conclusion

Based on the above analysis, the following conclusions may be drawn:

1. The total cost of road crashes is higher than that of casualties;
2. A crash-based approach is superior to a casualty-based approach that underestimates safety benefits;
3. A crash-based approach results in a wider range of countermeasures selected for implementation due to enhanced economic justification;
4. A crash-based approach does not change the priority of the countermeasures;
5. A more comprehensive countermeasure selection and prioritisation process is required to take into account budget constraints, road safety implementation works, discounting and full life cycle analysis.

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Appendices

Table A1

Infrastructure Improvement Program (Utrecht)

S/N	Countermeasure	Length / Sites	Fatalities & serious injuries saved	Present value of safety benefit (€)	Estimated Cost (€)	Program BCR
1	Signalised crossing	1 sites	10	3,233,649	45,000	72
2	Improve curve delineation	0.40 km	0.5	148,419	7,460	20
3	Sight distance (obstruction removal)	1.40 km	2	678,298	35,280	19
4	Pedestrian fencing	27.20 km	9	2,976,955	179,606	17
5	Street lighting (intersection)	14 sites	21	6,599,575	504,000	13
6	Refuge Island	14 sites	14	4,606,949	416,422	11
7	Shoulder rumble strips	199.30 km	84	27,156,276	2,382,592	11
8	Protected turn lane (unsignalised 4 leg)	3 sites	14	4,375,323	535,399	8
9	Unsignalised crossing	5 sites	4	1,230,100	217,465	6
10	Centreline rumble strip / flexi-post	1.80 km	0.3	108,423	19,512	6
11	Central hatching	5.70 km	0.6	184,481	34,173	5
12	Parking improvements	1.50 km	0.3	99,666	18,900	5
13	Improve Delineation	45.70 km	13	4,190,892	847,446	5
14	Traffic calming	2.90 km	1	370,148	87,581	4
15	Central median barrier (no duplication)	0.70 km	1	365,701	95,182	4
16	Protected turn lane (unsignalised 3 leg)	54 sites	74	23,918,473	7,210,571	3
17	Footpath provision driver side (adjacent to road)	27.90 km	35	11,319,681	4,388,280	3
18	Footpath provision passenger side (>3m from road)	26.80 km	29	9,267,974	3,085,368	3
19	Footpath provision driver side (>3m from road)	25.40 km	28	9,060,036	2,922,040	3
20	Bicycle Lane (off-road)	3.50 km	3	1,122,681	392,156	3
21	Footpath provision passenger side (informal path >1m)	5.80 km	1	406,768	141,451	3
22	Footpath provision driver side (informal path >1m)	4.70 km	1	307,139	114,747	3
23	Roadside barriers - driver side	206.20 km	199	64,041,774	27,898,500	2
24	Roadside barriers - passenger side	159.20 km	111	35,791,424	21,558,000	2
25	Footpath provision passenger side (adjacent to road)	44.10 km	52	16,843,531	6,939,120	2
26	Central median barrier (1+1)	34.80 km	41	13,286,137	6,288,200	2
27	Wide centreline	12.50 km	0.6	181,898	75,710	2
28	Delineation and signing (intersection)	8 sites	0.5	149,378	88,582	2
29	Road surface rehabilitation	0.80 km	0.4	115,173	70,435	2
30	Clear roadside hazards - driver side	0.10 km	0.1	34,232	20,000	2
31	Additional lane (2 + 1 road with barrier)	15.10 km	80	25,660,031	20,655,000	1
32	Shoulder sealing driver side (>1m)	103.50 km	40	12,712,184	9,156,140	1
33	Shoulder sealing passenger side (>1m)	71.50 km	29	9,428,574	6,334,720	1
34	Duplication with median barrier	1.20 km	26	8,323,159	6,480,000	1
35	Street lighting (mid-block)	10.30 km	4	1,352,702	1,483,200	1
36	Upgrade pedestrian facility quality	43 sites	3	826,756	767,405	1
37	Lane widening (up to 0.5m)	1.00 km	2	684,333	656,756	1
38	Overtaking lane	0.30 km	1	339,394	405,000	1
39	Shoulder sealing passenger side (<1m)	6.60 km	0.9	292,349	294,490	1
40	Protected turn provision at existing signalised site (4-leg)	1 sites	0.6	204,497	237,955	1
41	Lane widening (>0.5m)	0.10 km	0.6	186,272	152,529	1
42	Clear roadside hazards (bike lane)	1.20 km	0.5	160,633	216,000	1
43	Shoulder sealing driver side (<1m)	1.50 km	0.2	68,926	66,640	1
44	Side road signalised pedestrian crossing	1 sites	0.1	28,480	45,000	1
45	Street lighting (ped crossing)	2 sites	0.1	26,839	36,000	1

Source: (IRAP, 2021)

Table A2

Comparing the Cost of Crashes and Casualties

Country	Crashes					Casualties				Cost of crashes/Cost of casualties
	Fatal	Serious	Slight	PDO	Total cost of crashes (€)	Fatal	Serious	Slight	Total cost of casualties (€)	
Austria	429	9,262	26,917	646,553	7,920,295,531	523	10,502	34,522	5,316,828,892	1.49
Estonia	61	433	1,345	29,218	475,115,953	67	467	1,756	341,752,144	1.39
Finland	208	475	4,641	478,863	2,772,192,852	229	519	6,186	846,606,266	3.27
Germany	3,187	58,744	240,504	2,104,250	46,137,923,908	3,377	67,732	321,803	37,018,055,453	1.25
Iceland	16	155	741	5,500	145,082,415	16	178	1,130	121,247,886	1.20
Ireland	179	398	4,399	21,734	851,577,882	188	508	6,252	752,038,172	1.13
Norway	148	597	4,380	403,719	2,353,003,850	160	693	5,670	728,618,840	3.23
Slovenia	112	868	5,605	11,358	847,606,898	120	932	7,778	768,088,106	1.10
UK	1,658	20,676	123,988	2,232,305	24,996,617,407	1,775	22,807	169,895	15,599,586,275	1.60

Source: (Author's own computation)

Table A3

Countermeasures Selected using the iRAP Approach

S/N	Countermeasure	Length / Sites	Fatalities	Serious injuries	Safety benefit (€)	Estimated Cost (€)	Program BCR
1	Signalised crossing	1 sites	1.3	8.8	5,489,070	45,000	122
2	Improve curve delineation	0.40 km	0.1	0.4	274,454	7,460	37
3	Sight distance (obstruction removal)	1.40 km	0.3	1.8	1,097,814	35,280	31
4	Pedestrian fencing	27.20 km	1.1	7.9	4,940,163	179,606	28
5	Street lighting (intersection)	14 sites	2.6	18.4	11,527,047	504,000	23
6	Shoulder rumble strips	199.30 km	10.5	73.5	46,108,188	2,382,592	19
7	Refuge Island	14 sites	1.8	12.3	7,684,698	416,422	18
8	Protected turn lane (unsignalised 4 leg)	3 sites	1.8	12.3	7,684,698	535,399	14
9	Unsignalised crossing	5 sites	0.5	3.5	2,195,628	217,465	10
10	Central hatching	5.70 km	0.1	0.5	329,344	34,173	10
11	Parking improvements	1.50 km	0.0	0.3	164,672	18,900	9
12	Centreline rumble strip / flexi-post	1.80 km	0.0	0.3	164,672	19,512	8
13	Improve Delineation	45.70 km	1.6	11.4	7,135,791	847,446	8
14	Traffic calming	2.90 km	0.1	0.9	548,907	87,581	6
15	Central median barrier (no duplication)	0.70 km	0.1	0.9	548,907	95,182	6
16	Protected turn lane (unsignalised 3 leg)	54 sites	9.3	64.8	40,619,118	7,210,571	6
17	Footpath provision driver side (>3m from road)	25.40 km	3.5	24.5	15,369,396	2,922,040	5
18	Footpath provision passenger side (>3m from road)	26.80 km	3.6	25.4	15,918,303	3,085,368	5
19	Footpath provision driver side (informal path >1m)	4.70 km	0.1	0.9	548,907	114,747	5
20	Footpath provision driver side (adjacent to road)	27.90 km	4.4	30.6	19,211,745	4,388,280	4
21	Wide centreline	12.50 km	0.1	0.5	329,344	75,710	4
22	Bicycle Lane (off-road)	3.50 km	0.4	2.6	1,646,721	392,156	4
23	Footpath provision passenger side (adjacent to road)	44.10 km	6.5	45.5	28,543,164	6,939,120	4
24	Roadside barriers - driver side	206.20 km	24.9	174.1	109,232,493	27,898,500	4
25	Footpath provision passenger side (informal path >1m)	5.80 km	0.1	0.9	548,907	141,451	4
26	Central median barrier (1+1)	34.80 km	5.1	35.9	22,505,187	6,288,200	4

Source: (Author's own computation)

Table A4

Countermeasures Selected using the Casualty-based Approach (all Severity Levels)

S/N	Countermeasure	Length / Sites	Fatalities	Serious injuries	Slight injuries	Safety benefit (€)	Estimated Cost (€)	Program BCR
1	Signalised crossing	1 sites	1.3	8.8	56.4	7,035,172	45,000	156
2	Improve curve delineation	0.40 km	0.1	0.4	2.8	351,759	7,460	47
3	Sight distance (obstruction removal)	1.40 km	0.3	1.8	11.3	1,407,034	35,280	40
4	Pedestrian fencing	27.20 km	1.1	7.9	50.8	6,331,655	179,606	35
5	Street lighting (intersection)	14 sites	2.6	18.4	118.4	14,773,861	504,000	29
6	Shoulder rumble strips	199.30 km	10.5	73.5	473.7	59,095,445	2,382,592	25
7	Refuge Island	14 sites	1.8	12.3	78.9	9,849,241	416,422	24
8	Protected turn lane (unsignalised 4 leg)	3 sites	1.8	12.3	78.9	9,849,241	535,399	18
9	Unsignalised crossing	5 sites	0.5	3.5	22.6	2,814,069	217,465	13
10	Central hatching	5.70 km	0.1	0.5	3.4	422,110	34,173	12
11	Parking improvements	1.50 km	0.0	0.3	1.7	211,055	18,900	11
12	Centreline rumble strip / flexi-post	1.80 km	0.0	0.3	1.7	211,055	19,512	11
13	Improve Delineation	45.70 km	1.6	11.4	73.3	9,145,724	847,446	11
14	Traffic calming	2.90 km	0.1	0.9	5.6	703,517	87,581	8
15	Central median barrier (no duplication)	0.70 km	0.1	0.9	5.6	703,517	95,182	7
16	Protected turn lane (unsignalised 3 leg)	54 sites	9.3	64.8	417.3	52,060,273	7,210,571	7
17	Footpath provision driver side (>3m from road)	25.40 km	3.5	24.5	157.9	19,698,482	2,922,040	7
18	Footpath provision passenger side (>3m from road)	26.80 km	3.6	25.4	163.5	20,401,999	3,085,368	7
19	Footpath provision driver side (informal path >1m)	4.70 km	0.1	0.9	5.6	703,517	114,747	6
20	Footpath provision driver side (adjacent to road)	27.90 km	4.4	30.6	197.4	24,623,102	4,388,280	6
21	Wide centreline	12.50 km	0.1	0.5	3.4	422,110	75,710	6
22	Bicycle Lane (off-road)	3.50 km	0.4	2.6	16.9	2,110,552	392,156	5
23	Footpath provision passenger side (adjacent to road)	44.10 km	6.5	45.5	293.2	36,582,894	6,939,120	5
24	Roadside barriers - driver side	206.20 km	24.9	174.1	1122.2	139,999,922	27,898,500	5
25	Footpath provision passenger side (informal path >1m)	5.80 km	0.1	0.9	5.6	703,517	141,451	5
26	Central median barrier (1+1)	34.80 km	5.1	35.9	231.2	28,844,205	6,288,200	5
27	Road surface rehabilitation	0.80 km	0.1	0.4	2.3	281,407	70,435	4
28	Delineation and signing (intersection)	8 sites	0.1	0.4	2.8	351,759	88,582	4
29	Roadside barriers - passenger side	159.20 km	13.9	97.1	626.0	78,090,409	21,558,000	4
30	Clear roadside hazards - driver side	0.10 km	0.0	0.1	0.6	70,352	20,000	4

Source: (Author's own computation)

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Table A5

Countermeasures Selected using the Crash-based Approach

S/N	Countermeasure	Length / Sites	Fatal	Serious injury	Slight injury	PDO	Safety benefit (€)	Estimated Cost (€)	Program BCR
1	Signalised crossing	1 sites	1.2	7.7	41.9	397.5	8,829,598	45,000	196
2	Improve curve delineation	0.40 km	0.1	0.4	2.1	19.9	441,480	7,460	59
3	Sight distance (obstruction removal)	1.40 km	0.2	1.5	8.4	79.5	1,765,920	35,280	50
4	Pedestrian fencing	27.20 km	1.0	6.9	37.7	357.8	7,946,638	179,606	44
5	Street lighting (intersection)	14 sites	2.4	16.1	88.0	834.8	18,542,156	504,000	37
6	Shoulder rumble strips	199.30 km	9.8	64.5	352.1	3339.4	74,168,624	2,382,592	31
7	Refuge Island	14 sites	1.6	10.8	58.7	556.6	12,361,437	416,422	30
8	Protected turn lane (unsignalised 4 leg)	3 sites	1.6	10.8	58.7	556.6	12,361,437	535,399	23
9	Unsignalised crossing	5 sites	0.5	3.1	16.8	159.0	3,531,839	217,465	16
10	Central hatching	5.70 km	0.1	0.5	2.5	23.9	529,776	34,173	16
11	Parking improvements	1.50 km	0.0	0.2	1.3	11.9	264,888	18,900	14
12	Centreline rumble strip / flexi-post	1.80 km	0.0	0.2	1.3	11.9	264,888	19,512	14
13	Improve Delineation	45.70 km	1.5	10.0	54.5	516.8	11,478,478	847,446	14
14	Traffic calming	2.90 km	0.1	0.8	4.2	39.8	882,960	87,581	10
15	Central median barrier (no duplication)	0.70 km	0.1	0.8	4.2	39.8	882,960	95,182	9
16	Protected turn lane (unsignalised 3 leg)	54 sites	8.6	56.9	310.2	2941.8	65,339,026	7,210,571	9
17	Footpath provision driver side (>3m from road)	25.40 km	3.3	21.5	117.4	1113.1	24,722,875	2,922,040	8
18	Footpath provision passenger side (>3m from road)	26.80 km	3.4	22.3	121.6	1152.9	25,605,835	3,085,368	8
19	Footpath provision driver side (informal path >1m)	4.70 km	0.1	0.8	4.2	39.8	882,960	114,747	8
20	Footpath provision driver side (adjacent to road)	27.90 km	4.1	26.9	146.7	1391.4	30,903,593	4,388,280	7
21	Wide centreline	12.50 km	0.1	0.5	2.5	23.9	529,776	75,710	7
22	Bicycle Lane (off-road)	3.50 km	0.3	2.3	12.6	119.3	2,648,879	392,156	7
23	Footpath provision passenger side (adjacent to road)	44.10 km	6.0	39.9	218.0	2067.2	45,913,910	6,939,120	7
24	Roadside barriers - driver side	206.20 km	23.1	152.9	834.1	7911.1	175,709,003	27,898,500	6
25	Footpath provision passenger side (informal path >1m)	5.80 km	0.1	0.8	4.2	39.8	882,960	141,451	6
26	Central median barrier (1+1)	34.80 km	4.8	31.5	171.9	1629.9	36,201,352	6,288,200	6
27	Road surface rehabilitation	0.80 km	0.0	0.3	1.7	15.9	353,184	70,435	5
28	Delineation and signing (intersection)	8 sites	0.1	0.4	2.1	19.9	441,480	88,582	5
29	Roadside barriers - passenger side	159.20 km	12.9	85.3	465.3	4412.7	98,008,539	21,558,000	5
30	Clear roadside hazards - driver side	0.10 km	0.0	0.1	0.4	4.0	88,296	20,000	4
31	Shoulder sealing passenger side (>1m)	71.50 km	3.4	22.3	121.6	1152.9	25,605,835	6,334,720	4
32	Shoulder sealing driver side (>1m)	103.50 km	4.6	30.7	167.7	1590.2	35,318,393	9,156,140	4
33	Duplication with median barrier	1.20 km	3.0	20.0	109.0	1033.6	22,956,955	6,480,000	4

Source: (Author's own computation)

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CIVIL & ENVIRONMENTAL ENGINEERING | REVIEW ARTICLE

A systematic review of road safety investment appraisal models

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Abstract: It is estimated that 1.35 million people die annually due to road traffic crashes and these crashes cost most countries 3–5% of their gross domestic product (GDP). The economic appraisal of roads considers safety aspects to some extent, but a more explicit approach could add significant value. Therefore, in an attempt to develop a safety-focused model based on the life cycle of measures, this review examines the available models with the view of documenting the current knowledge and its gaps. The review followed the procedures and guidelines developed at the Evidence for Policy and Practice Information and Co-ordinating Centre (EPPI-Centre) together with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA). The searching and screening process resulted in 12 studies that documented and described the guidelines and methodological framework for SafetyAnalyst, Economic Efficiency Evaluation (E^3), the Benefit Cost Analysis (BCA) and the International Road Assessment Programme (iRAP) road safety models. There are no standardized methods for combining life cycle costs of road safety countermeasures during appraisal, and all approaches ignore end of infrastructure life costs. There is neither uniformity nor universally accepted standards to estimate crash or casualty unit costs and the life cycle performance of road safety countermeasures.

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PUBLIC INTEREST STATEMENT

Road safety is a major challenge worldwide with an estimated 1.35 million fatalities annually and these traffic crashes cost most countries 3–5% of their Gross Domestic Product (GDP). Road traffic crashes are largely preventable with a comprehensive package of cost-effective measures introduced through improved business cases. The need to scale up road safety investment to reduce the high social costs requires a model that can compute accurately the economic benefits of countermeasures. However, there is still a debate regarding the most accurate approach to determine crash costs, benefit from multiple treatments and costs of countermeasures. This systematic review identified and compared some of the models used with a view of documenting the current knowledge and gaps. The findings demonstrate lack of standardisation and uniformity in the approaches used. Therefore, enhancing the existing models or developing an advanced model to compute accurately the costs and benefits of countermeasures over their life cycle is required.

Subjects: Transport & Vehicle Engineering; Transportation Engineering; Engineering Economics

Keywords: Model; countermeasure; economic analysis; road safety; systematic review

1. Introduction

It is estimated that 1.35 million people die annually due to road traffic crashes ([WHO] World Health Organisation, 2018) that costs most countries 3–5% of their gross domestic product (GDP). In most cases, there are limited resources and budgets for implementing road safety countermeasures ([PIARC] Permanent International Association of Road Congresses, 2019). Therefore, a systematic process supporting safety infrastructure investment across the road network to produce the optimum safety benefit for the cost is urgent.

However, there has been considerable debate regarding the most accurate approach to determine crash costs, benefit from multiple treatments and costs of countermeasures ([PIARC] Permanent International Association of Road Congresses, 2019). Road traffic crashes are largely preventable provided that a comprehensive package of cost-effective measures are included in the planning, design and operation of the road network. To present improved business cases to scale up road safety investment and to reduce the high socio-economic price paid by society, an advanced model capable of calculating costs and benefits of road safety countermeasures over their life cycle is required.

The economic appraisal of roads is well-documented and supported by a number of models such as the Highway Development Management (HDM-4) model (Morosiuk & Kerali, 2001) developed by the World Bank where road safety aspects are to some extent considered. However, a more explicit approach could add significant value. Therefore, in an attempt to develop a safety-focused model based on the life cycle of countermeasures, a systematic literature review presented in this paper examined the available road safety investment appraisal models with the view to compare and contrast them and ultimately demonstrate the lack of standardization and uniformity in the approach used. This paper describes the results of the review and discusses the structure and principles of the identified models and the methods used to define the life cycle of road safety countermeasures.

2. Methods

2.1. Systematic review

A systematic literature review is an examination of the available evidence in a particular area of study based on a clearly formulated question and using a methodical approach to identify, select, critically appraise all the relevant studies, and synthesize the findings. The following questions guided this review: (i) what road safety investment appraisal models are available and used as decision support systems? (ii) What is the structure and principle of these models? (iii) What are the methods used to define the life cycle of road safety countermeasures? The procedures and guidelines developed by Gough et al. (2017) at the Evidence for Policy and Practice Information and Co-ordinating Centre (EPPI-Centre), a research unit at the Institute of Education, University College London, United Kingdom (UK), and the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009) were used in this review. The EPPI—Reviewer 4 tool (Thomas et al., 2010)—performed a number of tasks such as storing retrieved studies, screening and data extraction.

2.2. Search strategy

Twenty-two electronic bibliographic databases and 17 organization websites (Appendix A), search engines such as google, google scholar, etc. were searched using search terms (Appendix B) and search operators (phrase searching, truncation, brackets and adjacency or proximity). Boolean operators (AND/OR) were also used to combine the keyword searches. The snowballing technique using the reference lists of relevant studies also leads to other studies in this review. Finally, some key road safety professionals also shared some information regarding documentation and appropriate source of data.

2.3. Inclusion and exclusion criteria

Published, grey literature and studies in any country relating to the different concepts of the review questions in English language irrespective of the date of study and publication were included. Studies excluded in this review were those in other languages and those not related to road safety investment models or tools, investment appraisal and economic evaluation of road safety measures/countermeasures.

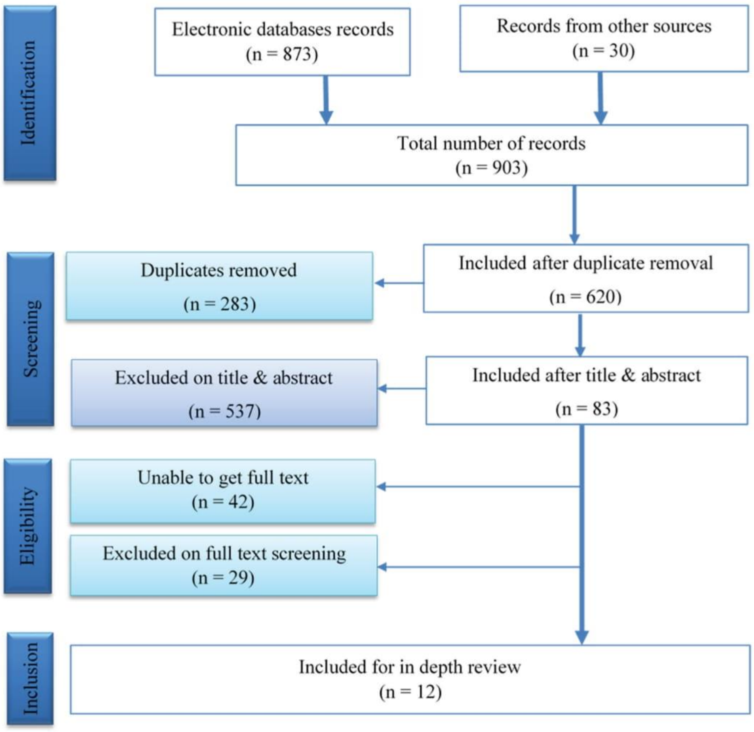
2.4. Synthesis

Ultimately, the data extracted from the included studies using the EPPI—Reviewer 4 software tools were organized and interpreted to answer the review questions, an approach referred to as configurative synthesis (Gough et al., 2017).

3. Results

The ultimate aim was to find longitudinal studies indicating the popularity of such models in road management systems used by the road industry. Searching resulted in 903 records (Figure 1) being uploaded into the review software. The results of the screening process as per the PRISMA guide

Figure 1. PRISMA flow chart for screening of studies.



(Moher et al., 2009) shown in Figure 1 resulted in 12 records meeting the inclusion criteria and thus considered for in-depth review. Of these 12 records, 2 records ([AASHTO] American Association of State Highway and Transportation Officials, 2020; Harwood et al., 2010) documented the SafetyAnalyst model and 4 records (Martensen et al., 2018; Martensen & Lassarre, 2017; Martensen et al., 2016; Van Den Berghe et al., 2017) described the guidelines and methodological framework for the Economic Efficiency Evaluation (E^3) model. The other 4 records ([iRAP] International Road Assessment Programme, 2013, 2015a, 2015b; McMahon & Dahdah, 2008) described the International Road Assessment Programme (iRAP) model and 2 records [FHWA] Federal Highway Administration, 2019; Lawrence et al., 2018) documented the Benefit Cost Analysis (BCA) model.

3.1. Question 1: Available road safety investment appraisal models

3.1.1. SafetyAnalyst model

SafetyAnalyst is a set of computerized analytical tools comprising network screening, diagnosis and countermeasure selection, economic appraisal and priority ranking, countermeasure selection and systemic site selection. The tool developed for the FHWA aids state and local highway agencies in the United States (US) in safety improvements (Harwood et al., 2010). The software is available for licensing by the AASHTO.

3.1.2. E^3 model

E^3 is a European Union (EU) standard model included in the Safety CaUsation, Benefits and Efficiency (SafetyCube) decision support system developed with funding from the European Commission under the Horizon 2020 research framework programme with support from 17 partners from 12 EU countries. The model performs economic evaluation of single measures related to infrastructure, vehicle and human behaviour and not programs of several countermeasures (Martensen et al., 2018).

3.1.3. BCA model

BCA is a model developed to support state and local highway agencies in the US to implement procedures described and documented in the Highway Safety Benefit Cost Analysis Guide developed by the FHWA Office of Safety. The model conducts simple economic analysis of infrastructure projects by quantifying costs as well as the direct and indirect safety-related benefits of project alternatives ([FHWA] Federal Highway Administration, 2019).

3.1.4. iRAP model

The iRAP model tackles challenging social and economic costs of road crashes. Risk maps, star ratings, safer roads investment plans (SRIP) and performance tracking are the four main protocols used in iRAP to assess and improve safety of roads. The iRAP performs economic analysis of single or multiple countermeasures during the preparation of SRIP ([iRAP] International Road Assessment Programme, 2015a). iRAP has conducted programmes in over 100 countries across Europe, Asia Pacific, North, Central and South America and Africa.

3.2. Question 2: Structure and principle of the models

The following criteria (Robinson, 2008) that distinguish modern road management systems were the basis in examining the constituent components of these models as summarized in Figure 2:

(1) Road network sectioning
(2) Intervention level
(3) Countermeasure options that may be considered
(4) Complexity of economic analysis and
(5) Countermeasures' prioritization method.

3.2.1. Road network sectioning

SafetyAnalyst divides the road network into road segments of variable lengths, ramps and intersections unlike iRAP that divides the road network into 100-metre road segments. The other two models (E^3 and BCA) appear not to consider such road management concepts.

3.2.2. Intervention level

SafetyAnalyst uses a crash-based approach whereby the crash frequencies are estimated using safety performance functions (SPFs). SPFs predict crash frequencies for all crash severity levels combined—i.e. fatal and all injury (FI) crashes—as a function of the annual average daily traffic (AADT). In contrast, iRAP uses a systemic approach whereby existing road attributes for every 100-metre segment are the basis for any intervention.

3.2.3. Countermeasure options

SafetyAnalyst provides for selection of a possible array of countermeasures based on the safety problem, crash summary statistics, collision diagrams, statistical crash frequency tests and analyst's knowledge. Similarly, iRAP considers multiple countermeasures for 100-metre segments of road based on a star rating system and road attributes. However, in iRAP, each countermeasure must generate a benefit cost ratio (BCR) exceeding a set threshold by the analyst and thus, the number of deaths and serious injuries prevented by each countermeasure are required in this process. The E^3 model analyzes single road safety measures, while the BCA model analyses a maximum of two countermeasures.

3.2.4. Complexity of economic analysis

Figure 2 shows the summary of the basis of the economic analysis conducted by these models. Fatal, serious injury, slight injury and property damage only (PDO) are the severity levels considered in the E^3 model. However, in SafetyAnalyst and BCA models, an additional severity level of possible injury is considered. The iRAP model analyzes only two severity levels (fatal and serious injury).

3.2.5. Countermeasures' prioritization methods

All the models use cost benefit and cost-effectiveness analyses except BCA that uses cost-benefit analysis only. In cost-benefit analysis, the costs of countermeasures and their monetized safety benefits determine the benefit-to-cost ratio (BCR) and the net present value (NPV) of the investment, where a countermeasure is economically justified if its BCR is greater than 1.0 and its NPV is a positive value. Cost-effectiveness is generally expressed as the money spent per reduced crash and countermeasures with lower cost per crash reduced are desirable.

3.3. Question 3: Methods for defining the life cycle of road safety countermeasures

Cost and performance of road safety countermeasures during their life cycle was the focus in answering this review question.

3.3.1. Cost of road safety countermeasures

In SafetyAnalyst (Harwood et al., 2010), an annual construction cost (ACC_v) in Equation (1) for implementing a single countermeasure is computed using its construction cost (CC_V) and a crash reduction factor (CRF) in Equation (2), obtained using service life (S_V) and annual rate of return or discount rate (R).

$$ACC_v = CC_V * CRF \quad (1)$$

$$CRF = \frac{R(1+R)^{S_v}}{(1+R)^{S_v} - 1} \quad (2)$$

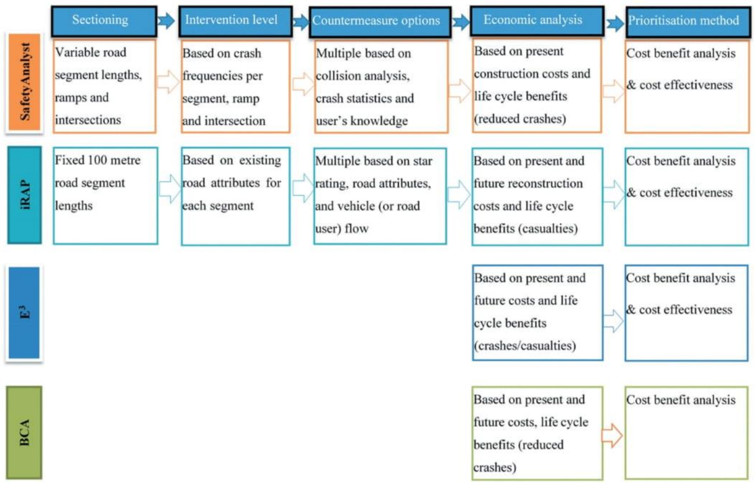


Figure 2. Structure of the models.

If multiple countermeasures implemented together with the same service lives, the combined cost is the sum of the construction costs of the individual countermeasures. According to [AASHTO] American Association of State Highway and Transportation Officials (2020), if the service lives are different assuming two countermeasures, the combined cost($CC_{(A+B)}$) in Equation (3) is

$$CC_{(A+B)} = (CC_A) + (CC_B)CRF(R, S_B)USPWF(R, S_A), \quad (3)$$

$$CRF(R, S_B) = \frac{R(1+R)^{S_B}}{(1+R)^{S_B} - 1}, \quad (4)$$

$$USPWF(R, S_A) = \frac{(1+R)^{S_A} - 1}{R(1+R)^{S_A}}. \quad (5)$$

where CC_A and CC_B are the costs of countermeasures with longer and shorter service lives, respectively, S_A and S_B are the longer and shorter service lives, respectively, and USPWF in Equation (5) is the uniform series present worth factor.

In the E^3 model (Martensen et al., 2016), the total cost equals the sum of one-time investment costs and running costs. The BCA model considers the total cost as the initial cost (project support, right of way and construction) plus subsequent costs for maintenance, operation, rehabilitation and mitigation. The model provides an adjustment in the case of two countermeasures by standardizing the service life using the least common multiple of the service lives, which becomes the analysis period.

In iRAP ([iRAP] International Road Assessment Programme, 2015a), the economic costs are construction and reconstruction costs based on service life data for each countermeasure. This method supports a typical analysis period of 20 years such that a countermeasure with a service life of 20 years gets constructed once, then the one with a service life of 10 years is constructed at the start and reconstructed 10 years later ([iRAP] International Road Assessment Programme, 2015b).

3.3.2. Performance of road safety countermeasures

Performance of the countermeasures over their life cycle is measured by effectiveness (E) given by Equation (6), which relates to the reduced number of crashes measured by a crash modification factor (CMF). A CMF is a multiplication factor, which indicates the number of crashes that would remain after implementing a countermeasure (Martensen & Lassarre, 2017),

$$E = 100(1 - \text{CMF}) \tag{6}$$

In the case of multiple countermeasures, SafetyAnalyst uses a single CMF value to represent the combined effect, which is simply the product of individual CMFs (Harwood et al., 2010). In BCA, when two countermeasures are applied to a crash of the same type and severity, they are analysed to decide whether the two are truly independent, have some overlap or have a counteractive effect. Then, the combined factor (CMF_c) is given by Equations (7), (8) and (9), respectively (Lawrence et al., 2018), where CMF_1 is the factor for the most effective countermeasure and $\text{CMF}_2$is for the second most effective countermeasure. In case of complete overlap, the dominant effect method that applies the most effective countermeasure is used.

$$\text{CMF}_c = 1 - [(1 - \text{CMF}_1) + (1 - \text{CMF}_2)], \tag{7}$$

$$\text{CMF}_c = (\text{CMF}_1 * \text{CMF}_2)^{\text{CMF}_1}, \tag{8}$$

$$\text{CMF}_c = \text{CMF}_1 * \text{CMF}_2. \tag{9}$$

The iRAP model ([iRAP] International Road Assessment Programme, 2013) makes use of a multiple countermeasure correction factor (MCCF) providing a reduction for each individual countermeasure given by Equation (10). Further illustration of this adjustment is available in iRAP.

$$\text{Reduction} = \text{Reduction}_{\text{SIMPLE}} * \text{MCCF}, \tag{10}$$

$$\text{MCCF} = \frac{\text{Reduction}_{\text{MULTIPLIED}}}{\text{Reduction}_{\text{ADDITIVE}}}. \tag{11}$$

3.4. Economic analysis applicability

To examine the economic analysis applicability of the models, the study analyzed cost components, valuation methods and crash or casualty unit costs. The crash unit costs were computed using the iRAP methodology and compared with those used in other models.

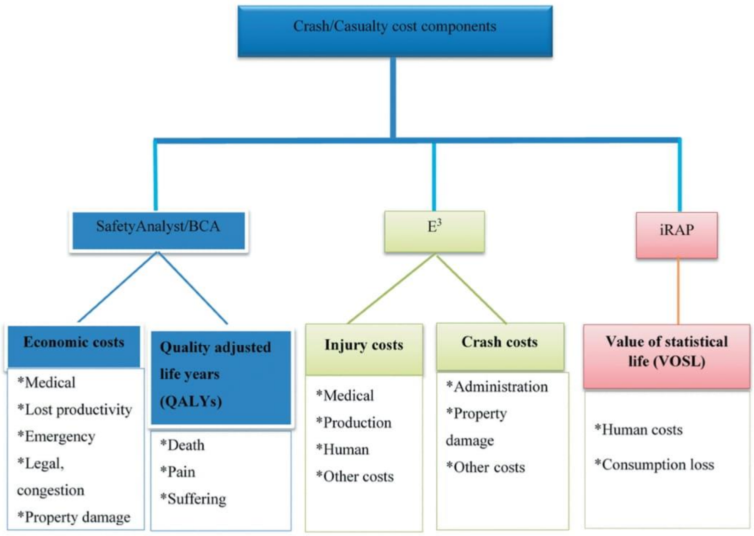
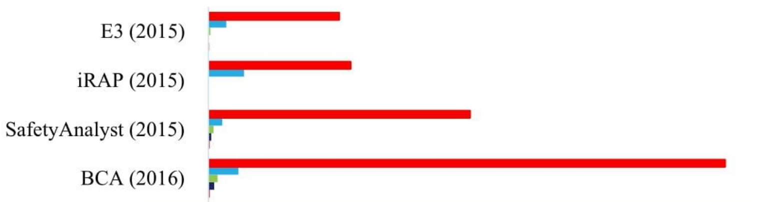


Figure 3. Crash/Casualty cost components for the models.



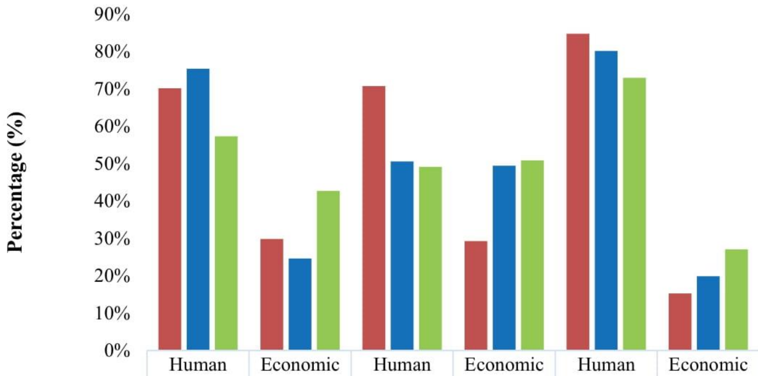
	BCA (2016)	SafetyAnalyst (2015)	iRAP (2015)	E3 (2015)
Fatal	11,295,400	5,722,300	3,114,650	2,862,789
Severe	655,000	302,900	778,663	389,384
Minor/Slight	198,500	110,700	-	41,447
Possible	125,600	62,400	-	-
PDO	11,900	10,100	-	4,396

Figure 4. Comparison between crash and casualty unit costs used in the models.

3.4.1. Cost components

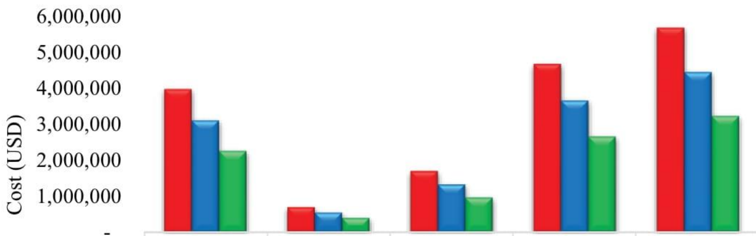
The review of the 4 models demonstrated that there are differences in the costing methods and components used (Figure 3). Accordingly, costs are generally sub-divided into human and economic or injury and crash-related costs. In addition, the terms direct and indirect costs are also used. In this review, the terms human and economic costs distinguish between these cost components.

Figure 5. Comparison between economic and human costs used in the models.



	E3 (2015)		SafetyAnalyst (2015)		BCA (2016)	
	Human Costs	Economic costs	Human Costs	Economic costs	Human Costs	Economic costs
Fatal	70%	30%	71%	29%	85%	15%
Severe	75%	25%	51%	49%	80%	20%
Minor/Slight	57%	43%	49%	51%	73%	27%

Figure 6. Computed fatal crash unit costs using VOSL and percentages of economic costs.



	VOSL	Economic costs		Comprehensive costs	
		Lower (15%)	Upper (30%)	Lower Limit	Upper Limit
US	3,976,245	701,690	1,704,105	4,677,935	5,680,350
UK	3,114,650	549,644	1,334,850	3,664,294	4,449,500
EU	2,262,362	399,240	969,584	2,661,602	3,231,945

3.4.2. Cost valuation methods

3.4.2.1. Cost of fatalities. In SafetyAnalyst, BCA and E^3 models, the willingness to pay (WTP) approach is the basis in estimating human cost of fatalities. A WTP approach is an attempt to estimate how much money an individual (Individual WTP) or the society as a whole (Social WTP) is willing to pay for a crash risk reduction (Schoeters et al., 2017). In determining individual WTP, the revealed preference (RP) and the stated preference (SP) methods are used to trade-off between money and the risk reduction. The RP methods, commonly used in the US, value risk based on actual behaviour, while the SP methods, preferred in Europe, use questionnaires to ask respondents how much they are willing to pay for more safety. However, in other studies, the gross output, net output, life insurance, court award and implicit public sector valuation approaches have been used (Jacobs, 1995).

3.4.2.2. Cost of non-fatalities. Information regarding the cost of non-fatalities is relatively poor, as many studies have focused on the VOSL, which leads to the estimation of human costs of fatalities (Schoeters et al., 2017). The cost of a serious injury as a percentage of VOSL is 10–16% by Wijnen et al. (2017) and 20–30% by McMahon and Dahdah (2008). Generally, the E^3 model recommends the WTP approach to determine the cost of non-fatalities relative to VOSL. However, in the US, where the BCA model is used, QALYs approach values non-fatal injuries by the duration and severity of the health problem. The costs for the non-fatal injured victims are in terms of the maximum abbreviated injury scale (MAIS), body part and type of fracture or dislocation (Zaloshnja et al., 2004).

3.4.2.3. Crash and casualty costs. Figure 4 presents unit costs for iRAP (computed for UK), SafetyAnalyst (Harmon et al., 2018) and BCA (Harmon et al., 2018) and E^3 (Wijnen et al., 2017) models. In order to compare the differences in the costs considered by each of the four models, the iRAP values were computed for UK based on the formula that the value of a fatality is 70 times the GDP per capita and that of a serious injury is equal to 25% of the value of a fatality (McMahon & Dahdah, 2008). The GDP per capita for UK (US$44,495) for 2015 (Statista, 2019) was used. Furthermore, Figure 5 shows the percentages of economic and human costs computed using data by Harmon et al. (2018) and Wijnen et al. (2017). The comprehensive crash unit cost for a fatality (Figure 6) was computed for UK, EU and US based on the iRAP methodology using the 2015 GDP per capita for the US ($56,804), EU ($32,319) and UK ($44,495). Based on the computed VOSL and using the iRAP methodology, the value of a serious injury is US$ 994,061 for US and US$565,590 for EU.

4. Discussion

This systematic review sought to capture the global practice in the utilisation of road safety economic models as part of road management systems. The review might not have identified all the relevant studies due to limitations in the search strategy; for example, some scholarly literature may not be in English or included in the databases considered. However, there are reasons to believe that the review discovered the main knowledge currently available. Subsequently, the simple demonstration based on the review showed that the methods used worldwide in determining the cost and performance of road safety countermeasures during their life cycle are not many and not fully consistent and harmonized.

The SafetyAnalyst and iRAP are comprehensive decision support tools used for the implementation of safety management plans. Conversely, BCA and E^3 appear to be mere economic analysis models. In addition, the systemic approach (based on existing road attributes) in iRAP appears to be more practical than the SafetyAnalyst's crash-based and may result in improved network safety in the long run as compared to the crash-based approach.

E^3 analyses a single countermeasure, the BCA model may consider up to two measures and both SafetyAnalyst and iRAP models can consider multiple countermeasures. This limits the applicability of the first two models because in practice, a combination of countermeasures may be implemented at a section and junction and in a road network. However, the iRAP model may also be considered as limited because it takes into account only 2 severity levels (fatal and serious injuries) compared to at least 4 severity levels in BCA, SafetyAnalyst and E^3 models. Furthermore, to determine the combined effect of multiple countermeasures, the multiplicative approach using CMFs is common although it tends to overestimate safety benefits in some studies ([PIARC] Permanent International Association of Road Congresses, 2019).

There is no uniformity in all models regarding their economic analyses. The SafetyAnalyst and BCA models utilise crash unit costs, whereas iRAP uses casualty unit costs. The E^3 model conducts analysis for either crashes or casualties. Crash and casualty unit costs used in all the models are not directly comparable. For example, the cost of serious injuries as a percentage of VOSL varies between 10 and 30%. Furthermore, computed unit cost for serious injuries for EU and US is higher than all the serious injury crash unit costs used in the models, implying that the iRAP methodology may be overestimating the unit cost of a serious injury. The BCA crash costs appear to be unrealistic since fatal crash costs computed for the US and the EU using the iRAP methodology are on average comparable with those used by SafetyAnalyst and E^3 models unlike those by the BCA model. All the models consider the human and economic costs in their cost components except iRAP that considers only human costs. Further analysis shows that human costs have a major share over the total crash cost and on average up to 70% compared to 30% of other economic costs.

The computation of countermeasure costs during appraisal differs in all methods and the end-of-life costs are not considered. Ideally, a life cycle approach should consider all the costs incurred during planning, design, building/construction, operation, maintenance and disposal in road project appraisal. SafetyAnalyst's cost computation approach offers the strength of an annualised cost method, which may be applicable to multiple treatments with unequal service lives. Finally, the indirect benefits related to reduced travel delays, VOC and emissions appear only in the BCA tool, making it unique compared to other models.

5. Conclusions

The main findings of this systematic review and subsequent analysis are as follows:

(1) SafetyAnalyst, BCA, E^3 and iRAP are the most widely used road safety investment appraisal models.

(2) SafetyAnalyst and iRAP are comprehensive decision support tools unlike BCA and E^3 that appear to be economic analysis models.

(3) The BCA and E^3 models have limited application because they consider a single or up to two countermeasures, whereas the SafetyAnalyst and iRAP models can analyze multiple countermeasures.

(4) It appears that there is neither uniformity nor universally accepted standards to compute the crash or casualty unit costs as well as the cost and performance of road safety countermeasures during their life cycle.

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Appendix A Electronic bibliographic databases

Web of Science, Ovid (Medline and EMBASE), EBSCOhost, ProQuest, SCOPUS, Cochrane, Barbour Environment Health and Safety, CIS (Construction Information service), Taylor and Francis, Concrete vault, Engineering Handbooks Online, Espacenet, GEOBASE & Compendex (Ei Village 2), Intellectual Property Office, Knovel, TRIS (Transport Research Information services), ITRD (International Transport Research Documentation), SafetyLit, ICE Virtual Library, OECD iLibrary, Business and Intellectual Property Centre—the British Library, and United States Patent and Trade Mark Office.

Organisation websites

World Road Association/PIARC, iRAP—the International Road Assessment Programme, World Bank/IDA, World Health Organization (WHO), DFID—UK Department for International Development, TRL Limited—Transport Research Laboratory, UK, AfDB—African Development Bank Group, EuropeAid—European Commission Cooperation Office, SWOV—Institute for Road Safety Research, the Netherlands, VTI—Swedish National Road and Transport Research Institute, TOI—Norway Institute of Transport Economics, AAA Foundation for Traffic Safety, ARRB—Australian Road Research Board, ITE—Institute of Transportation Engineers, ICE—Institute of Civil Engineers, US Department of Transport—Federal Highway Administration (USA) and NHTSA—National Highway Traffic Safety Administration, USA.

Appendix B Search terms

WEB OF SCIENCE (02/12/2019)

Road safety near/3 (measure* OR countermeasure* OR intervention* OR infrastructure* or engineering), Road* investment near/3 (appraisal OR economic* OR model OR tool, Road safety near/4 (appraisal OR economic* OR investment* OR tool OR model), "Road safety" OR "Traffic safety" OR "Accident prevention" OR "Road transport safety" OR "Highway safety" OR "Road user safety." (Appraisal investment) OR (Socio economic*) OR (Cost-Benefit Analysis*) OR (Cost-Effectiveness*) OR (Investment assessment*) OR (Investment evaluation).

OVID—MEDLINE AND EMBASE (02/12/2019)

("Road* safety countermeasure*" or "Road* safety intervention*" or "Road* safety infrastructure*"), ("Accident* measure*" or "Accident* countermeasure*" or "Accident* intervention*"). (Traffic safety adj3 (measure* or countermeasure* or intervention* or infrastructure*)). ("Investment appraisal" or "Socio economic*" or "Cost-Benefit Analysis*" or "Cost-Effectiveness" or "Investment assessment*" or "Investment evaluation*"). (Road safety adj4 (appraisal or economic* or investment* or tool or model)).

EBSCOhost (02/12/2019)

(Road safety countermeasure*) OR (Road safety measure*) OR (Traffic safety measure*) OR (Road safety Intervention*) OR (Road traffic safety measure*) OR (Accident prevention measure*) OR (Road safety engineering infrastructure*) OR (Road safety infrastructure*) OR (Safety engineering measure*). ("Investment appraisal") OR ("Socio economic*") OR ("Cost-Benefit Analysis*") OR ("Cost—Effectiveness") OR ("Investment assessment*") OR ("Investment evaluation*"). (Road safety investment model*) OR (Appraisal investment model*) OR (Socio-economic model*) OR (Cost-Benefit model*) OR (Cost-Benefit Analysis model*) OR (Cost—Effectiveness model*) OR (Investment assessment model*) OR (Investment evaluation model*).

PROQUEST (02/12/2019)

(("Road* safety countermeasure*") OR ("Road* safety intervention*") OR ("Road* safety infrastructure*") OR ("Road* traffic countermeasure*") OR ("Road* traffic intervention*") OR ("Road* traffic infrastructure") OR ("Accident* measure*") OR ("Accident* countermeasure*") OR ("Accident* intervention*") AND (("Investment appraisal") OR ("socio economic") OR ("socio economical") OR ("socio economically") OR ("socio economics") OR ("Cost-Benefit Analysis*") OR ("Cost Effectiveness") OR ("Investment assessment*") OR ("Investment evaluation*")).

SCOPUS (03/12/2019)

((("Road* safety countermeasure*" OR "Road* safety intervention*" OR "Road* safety infrastructure*")) OR (("Road* traffic countermeasure*" OR "Road* traffic intervention*" OR "Road* traffic infrastructure")) OR (("Accident* measure*" OR "Accident* countermeasure*" OR "Accident* intervention*"))) AND (("Investment appraisal" OR "Socio economic*" OR "Cost-Benefit Analysis*" OR "Cost—Effectiveness" OR "Investment assessment*" OR "Investment evaluation*")) ("Investment appraisal" OR" Socio economic*" OR" Cost-Benefit Analysis*" OR" Cost-effectiveness" OR" Investment assessment*" OR" Investment evaluation*").

TAYLOR AND FRANCIS (04/12/2019)

[road] AND [safety] AND [model] OR [appraisal] AND [measures], [road] AND [safety] AND [[appraisal] OR [tool]], [road] AND [[appraisal] OR [tool]]

GEOBASE & COMPENDEX (Ei VILLAGE 2) (04/12/2019)

(((($ROAD $SAFETY $INVESTMENT $MODEL) AND ((($Road $safety OR $appraisal OR economic* OR investment* OR $tool OR $model))). (((($Road $safety $investment $appraisal OR $Road $safety $tool OR $Road $safety $model) OR ((({Investment appraisal} OR {Socio economic*} OR {Cost Benefit Analysis*} OR {Cost—Effectiveness} OR {Investment assessment*} OR {Investment evaluation*}))). (("Road* safety countermeasure*" OR "Road* safety intervention*" OR "Road* safety infrastructure*" OR "Road* traffic countermeasure*" OR "Road* traffic intervention*" OR "Road* traffic infrastructure" OR "Accident* measure*" OR "Accident* countermeasure*" OR "Accident* intervention*")). ((Road safety investment appraisal OR Road safety tool OR Road safety model)), (((($Road $safety OR $appraisal OR economic* OR investment* OR $tool OR $model) AND ((((((($Road $safety $investment $appraisal OR $Road $safety $tool OR $Road $safety $model) OR ((({Investment appraisal} OR {Socio economic*} OR {Cost-Benefit Analysis*} OR {Cost—Effectiveness} OR {Investment assessment*} OR {Investment evaluation*}) AND (((((({Road safety} OR {Traffic safety} OR {Accident prevention} OR {Road transport safety} OR {Highway safety} OR {Road user safety}) OR (((({Road* safety countermeasure*} OR {Road* safety intervention*} OR {Road* safety infrastructure*} OR {Road* traffic countermeasure*} OR {Road* traffic intervention*} OR {Road* traffic infrastructure} OR {Accident* measure*} OR {Accident* countermeasure*} OR {Accident* intervention*})

APPENDIX B: SEARCH TERMS

WEB OF SCIENCE (02/12/2019)

Road safety near/3 (measure* OR countermeasure* OR intervention* OR infrastructure* or engineering), Road* investment near/3 (appraisal OR economic* OR model OR tool, Road safety near/4 (appraisal OR economic* OR investment* OR tool OR model), "Road safety" OR "Traffic safety" OR "Accident prevention" OR "Road transport safety" OR "Highway safety" OR "Road user safety".(Appraisal investment) OR (Socio economic*) OR (Cost Benefit Analysis*) OR (Cost - Effectiveness*) OR (Investment assessment*) OR (Investment evaluation).

OVID - MEDLINE AND EMBASE (02/12/2019)

("Road* safety countermeasure*" or "Road* safety intervention*" or "Road* safety infrastructure*"), ("Accident* measure*" or "Accident* countermeasure*" or "Accident* intervention*"). (Traffic safety adj3 (measure* or countermeasure* or intervention* or infrastructure*)). ("Investment appraisal" or "Socio economic*" or "Cost Benefit Analysis*" or "Cost – Effectiveness" or "Investment assessment*" or "Investment evaluation*").(Road safety adj4 (appraisal or economic* or investment* or tool or model)).

EBSCOhost (02/12/2019)

(Road safety countermeasure*) OR (Road safety measure*) OR (Traffic safety measure*) OR (Road safety Intervention*) OR (Road traffic safety measure*) OR (Accident prevention measure*) OR (Road safety engineering infrastructure*) OR (Road safety infrastructure*) OR (Safety engineering measure*).(“Investment appraisal”) OR (“Socio economic*”) OR (“Cost Benefit Analysis*”) OR (“Cost – Effectiveness”) OR (“Investment assessment*”) OR (“Investment evaluation*”). (Road safety investment model*) OR (Appraisal investment model*) OR (Socio-economic model*) OR (Cost Benefit model*) OR (Cost Benefit Analysis model*) OR (Cost - Effectiveness model*) OR (Investment assessment model*) OR (Investment evaluation model*).

PROQUEST (02/12/2019)

(("Road* safety countermeasure*") OR ("Road* safety intervention*") OR ("Road* safety infrastructure*") OR ("Road* traffic countermeasure*") OR ("Road* traffic intervention*") OR ("Road* traffic infrastructure") OR ("Accident* measure*") OR ("Accident* countermeasure*") OR ("Accident* intervention*") AND (("Investment appraisal") OR ("socio economic") OR ("socio economical") OR ("socio economically") OR ("socio economics") OR ("Cost Benefit Analysis*") OR ("Cost Effectiveness") OR ("Investment assessment*") OR ("Investment evaluation*")).

SCOPUS (03/12/2019)

((("Road* safety countermeasure*" OR "Road* safety intervention*" OR "Road* safety infrastructure*")) OR (("Road* traffic countermeasure*" OR "Road* traffic intervention*" OR "Road* traffic infrastructure")) OR (("Accident* measure*" OR "Accident* countermeasure*" OR "Accident* intervention*"))) AND (("Investment appraisal" OR "Socio economic*" OR "Cost Benefit Analysis*" OR "Cost -- Effectiveness" OR "Investment assessment*" OR "Investment evaluation*")). ("Investment appraisal" OR" Socio economic*" OR" Cost Benefit Analysis*" OR" Cost effectiveness" OR" Investment assessment*" OR" Investment evaluation*").

TAYLOR AND FRANCIS (04/12/2019)

[road] AND [safety] AND [model] OR [appraisal] AND [measures], [road] AND [safety] AND [[appraisal] OR [tool]], [road] AND [[appraisal] OR [tool]]

GEOBASE & COMPENDEX (Ei VILLAGE 2) (04/12/2019)

(((($ROAD $SAFETY $INVESTMENT $MODEL) AND ((($Road $safety OR $appraisal OR economic* OR investment* OR $tool OR $model))). (((($Road $safety $investment $appraisal OR $Road $safety $tool OR $Road $safety $model) OR ((({Investment ap-praisal} OR {Socio economic*} OR {Cost Benefit Analysis*} OR {Cost – Effectiveness} OR {Investment assessment*} OR {Investment evaluation*}))). (("Road* safety coun-termeasure*" OR "Road* safety intervention*" OR "Road* safety infrastructure*" OR "Road* traffic countermeasure*" OR "Road* traffic intervention*" OR "Road* traffic in-frastructure" OR "Accident* measure*" OR "Accident* countermeasure*" OR "Accident* intervention*")). ((Road safety investment appraisal OR Road safety tool OR Road safety model)), (((($Road $safety OR $appraisal OR economic* OR investment* OR $tool OR $model) AND ((((((($Road $safety $investment $appraisal OR $Road $safety $tool OR $Road $safety $model) OR ((({Investment appraisal} OR {Socio economic*} OR {Cost Benefit Analysis*} OR {Cost – Effectiveness} OR {Investment assessment*} OR {Investment evaluation*}) AND (((((({Road safety} OR {Traffic safety} OR {Accident prevention} OR {Road transport safety} OR {Highway safety} OR {Road user safety}) OR ((({Road* safety countermeasure*} OR {Road* safety intervention*} OR {Road* safety infrastructure*} OR {Road* traffic countermeasure*} OR {Road* traffic interven-tion*} OR {Road* traffic infrastructure} OR {Accident* measure*} OR {Accident* coun-termeasure*} OR {Accident* intervention*})

APPENDIX C: DATABASES AND ORGANISATIONAL WEBSITES

Electronic bibliographic databases

Web of Science, Ovid (Medline and EMBASE), EBSCOhost, ProQuest, SCOPUS, Cochrane, Barbour Environment Health and Safety, CIS (Construction Information service), Taylor and Francis, Concrete vault, Engineering Handbooks Online, Espacenet, GEOBASE & Compendex (Ei Village 2), Intellectual Property Office, Knovel, TRIS (Transport Research Information services), ITRD (International Transport Research Documentation), SafetyLit, ICE Virtual Library, OECD iLibrary, Business and Intellectual Property Centre – the British Library, and United States Patent and Trade Mark Office.

Organisation websites

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