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# "PREPARATION OF MULTI-YEAR WORKS PROGRAM USING MULTI-CRITERIA ANALYSIS"

**A THESIS**

*Submitted by*

**MUNYAMPENDA Imena (REG.NO: PG 20135054)**

*Under the Guidance of*

**Associate Professor Jennaro Odoki**

*Submitted in partial fulfilment of the requirements for the award of*

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**DEPARTMENT OF CIVIL ENGINEERING AND ENVIRONMENTAL TECHNOLOGY**
**SCHOOL OF ENGINEERING**
**(Nyarugenge Campus)**
**COLLEGE OF SCIENCE AND TECHNOLOGY**
**P.O. Box: 3900 Kigali, Rwanda**
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## COLLEGE OF SCIENCE AND TECHNOLOGY

Avenue de l'Armée, B.P. 3900 Kigali, Rwanda

## SCHOOL OF ENGINEERING

**DEPARTMENT OF**

**CIVIL ENGINEERING AND ENVIRONMENTAL TECHNOLOGY**


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This is to certify that the Thesis Work entitled **"Preparation of multi-year works program using Multi-Criteria Analysis"** *is a record of the original bonafide work done by* **MUNYAMPENDA Imena (REG.NO: PG 20135054)** in partial fulfillment of the requirement for the award of Masters of Science Degree in Transportation engineering and Economics at College of Science and Technology, University of Rwanda during the Academic Year 2012-2013**.**

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**SUPERVISOR**                **HEAD**

**Associate Professor Jennaro Odoki**                Dept. of CE & ET

*Submitted for the Project Examination held at UR-CST on ……… ……… ……… ….*

## DECLARATION

I hereby declare that the thesis entitled "**Preparation of multi-year works program using Multi-Criteria Analysis** " submitted for the Degree of Master of Science is my original work and the thesis has not formed the basis for the award of any Degree, Diploma, Associateship, Fellowship of similar other titles. It has not been submitted to any other University or Institution for the award of any Degree or Diploma.

Place: Kigali City
Signature:

Date: 25th July 2014
Name: Imena MUNYAMPENDA

**DEPARTMENT OF CIVIL ENGINEERING AND ENVIRONMENTAL TECHNOLOGY SCHOOL OF ENGINEERING**
**(Nyarugenge Campus)**

**COLLEGE OF SCIENCES AND TECHNOLOGY**
**P.O. Box: 3900 Kigali, Rwanda.**

## BONAFIDE CERTIFICATE

Certified that this thesis titled "**Preparation of multi-year works program using Multi-Criteria Analysis"** is the bonafide work of **MUNYAMPENDA Imena (REG.No: PG: 20135054)** who carried out the research under my supervision. Certified further that to the best of my knowledge the work reported herein does not form part of any other thesis or dissertation on the basis of which a degree or award was conferred on an earlier occasion for this or any other candidate.

Signature of the Supervisor:
Supervisor: Associate Professor Jennaro Odoki
Academic Designation: Professor
Department: **Civil Engineering and Environmental Technology.**
**College of Sciences and Technology**
**School of Engineering (Nyarugenge Campus)**
**P.O. Box: 3900 Kigali, Rwanda**

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## Abstract

A systematic approach to evaluate and rank projects for the one or rolling fiscal year may have a significant influence on road agencies effectiveness and efficiency to manage road network. In practice, road agencies have prioritized road projects based on subjective judgment. In order to efficiently manage the constraint budget for road works, Multi-Criteria inventory classification is used.

Analytical Hierarchy Process (AHP) is one of the best ways for evaluating and making a protocol of prioritization when different projects have to be compared to a set of criteria structure in different levels. Fuzzy Analytical Hierarchy Process (FAHP) is a synthetic extension of classical AHP method when the fuzziness of the decision makers is considered.

In this paper, a comparative analysis of AHP and FAHP for multi-criteria inventory classification model has been presented. The models developed are applied in the Rwanda National Paved Road Network to make a three years rolling maintenance road works programme.

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## ACRONYMS

**AHP** : Analytical Hierarchy Process

**CBA** : Cost Benefit Analysis

**CEA** : Cost Effectiveness Analysis

**DCLG** : Department for Communities and Local Government, Great Britain

**EIA** : Environmental Impact Assessment

**ELECTRE** : Elimination Et Choix Traduisant la Réalité

**IRR** : International Roughness Index

**MAUT** : Multi Attribute Utility Theory

**MCA** : Multi Criteria Analysis

**MCDM** : Multi-Criteria Decision Making

**NATA** : New Approach to Appraisal

**NEPA** : National Environment Policy Act

**NIS** : Negative ideal Solution

**RMF** : Road Maintenance Fund

**RMS** : Road Management System

**RNPR** : Rwanda National Paved Road Network

**RTDA** : Rwanda Transportation Development Agency

**NSRNS** : National Secondary Road Needs Study

**PIS** : Positive Ideal Solution

**PROMETHEE:** Preference Ranking Method for Enrichment Evaluations

**SEA** : Strategic Environmental Assessment

**SMCE** : Social multi-Criteria Evaluation

**TOPSIS** : Technique for Ordering Preference by Similarity to Ideal Solution

**UK** : United Kingdom

**UNESCO** : United Nation Educational, Scientific and Cultural Organization

# I. INTRODUCTION

## 1.1 General Introduction

The road network is an important asset for any country as it serves as the platform for economic and social development by supporting both regional development integration and the distribution of basic necessity of the people [1]. This expensive and important asset needs to be preserved and maintained to keep the purpose of its provision, which is to keep open the road network to continue to provide maximum capacity [1], through proper road maintenance investment framework.

The road investment is traditionally seen as the provision of both construction of new infrastructure and its maintenance [2]. A road, after construction, will be subjected to deterioration; this deterioration is function of factors such as traffic volume and loading, pavement design and construction quality, environmental weather and inefficient drainage system over time [3]. Thus maintenance and rehabilitation of the road infrastructure is highly necessary to be carried out periodically and strategically to keep the road functional and open for its designed purpose.

Due to budget constraint and high needs for road works compared to available resources, Road Agencies have to prepare an annually or rolling year programme budget for road works for the part or entire the road network [4]. This needs a road investment appraisal, with appraisal meaning evaluation and ranking of different alternatives. In this research, alternatives are road sections of Rwanda paved road network which competing to be maintained and they will be compared according different criteria for proper decision making.

The maintenance expenditure estimates for different remedial treatment works will be undertaken by the road agency officials. Since yearly budget for roads is limited and cannot cover all the selected sections proposed to be maintained or rehabilitated; a protocol to prioritize is highly needed and will take into account available resources. The selection of prioritized projects for the multi-year road works programme, either for the next budget year or for a couple of years, requires a suitable methodology based on sounded selected criteria.

For many years, monetary valuation for projects has been majorly used as a decision making tools for the road investment appraisal using both Cost-Benefit Analysis (CBA) and Cost Effectiveness Analysis (CEA). Those monetary evaluation methods have been criticized in transport appraisal as decision making tools as it ranks projects only in term of their economic efficiency and forgetting other impacts such as social, sustainability and equity [5].

The multi-criteria analysis (MCA)-type approach in transport appraisal as decision making tools is suitable as it considers the diverse nature of project impacts. This research project used MCA approach for evaluation and ranking projects even if its application in road investment analysis is still limited [3].

There exist two shortcoming of MCA; the first is that the ranking of projects in MCA depends on the decision makers' preferences and does not reflect the social preference in general, thus weights in MCA have been criticized to be arbitrary and are subjected to change [6]. The second shortcoming of MCA is that generally decision-makers require measures for value of money as well [7].

## 1.2 Objectives

This research aims to develop novel scoring function framework for appraisal and ranking projects to be used for preparing multi-year rolling of road maintenance works programme using Rwanda as a case study. The framework will assist decision makers to make an efficient preventive (not responsive) planning of works under insufficient budget while achieving the political goals and objectives.

The specific Objectives are:

1. To develop a road works programme model based on **Analytical Hierarchical Process (AHP)** method and analyze its stability and robustness,
2. To develop a road works programme model based on **Fuzzy Analytical Hierarchical Process (Fuzzy-AHP)** method and analyze its stability and robustness,
3. To **compare the results of the two MCA** models developed by assessing the impact on road network condition and determine which model yields best results.

## 1.3 Research Questions

In this study, the following questions will be answered:

1. Can AHP and Fussy AHP MCA methods be used to develop road works programme?
2. Are those two MCA methods stable and robust?
3. Which of those two methods give the best solution for road works programme?

## 1.4 Scope of the Study

The scope of this work is limited to the application of MCA in the preparation of multi-year, three years, for road maintenance works programme using Rwanda National Paved Road Network (RNPRN) as case study; with the objective of identifying routes or sections in RNPRN that are suitable for investment to maintain or rehabilitate and to develop a prioritized list of routes for investment for each year based on policy framework in Rwanda.

## 1.5 Structure of the thesis

The proposed methodology is organized into four stages:

In the first stage, we review road works management and planning preparation mechanism used worldwide. Also we will review, in this stage, MCA methods to identify which one that can be used in this work; as there are many MCA methods which have been applied in transport project.

Secondly, we will carry out a public questionnaires survey among the public institution staff management, academic staff and private stakeholders to get their view for weight scoring for the selected criteria set. The numeric weight for each criterion is based on the sum of four radical different scoring systems: economic development score, transportation efficiency score, road safety score and environmental score.

Thirdly, we will apply the designed scoring method on our sampled data. The use of the two MCA methods to aggregate score will be done at this stage.

The last stage will consist of carrying out a sensitivity analysis to assess the robustness of the two methods and compare them to get the strength and weakness of each method, and to recommend which method is stronger and more robust.

# II. Literature Review

## 2.1 Road Management System (RMS) :

### 2.1.1. Definitions and Generalities

Road Works Programming is one of the management functions that can be performed using the Road Management System (RMS). The RMS is based on the concept of 'engineering system' and 'management techniques' [8] and [9] Pinard et al (1998) defined it as a '*structured system employing a set of formalised procedures to evaluate alternative strategies in a systematic and coordinated manner with the objective of providing, maintaining and managing a road system at minimum cost and maximum efficiency*'.

The Organization for Economic Co-Operation and Development [6] develops a common definition of RM, and defines it as "*A systematic process of maintaining, upgrading and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organized and flexible approach to making the decisions necessary to achieve the public's expectations*."

RMS is composed of all the processes, tools, data and policies necessary to select and prioritize road works projects; according to the World Bank Group [10]. RMS is composed of two components:

1. An **Information System**, to collect, to organize and to manage data and information of the road network.
2. The **Decision-Support Systems** (DSS), to process the data and provide the information on which decisions can be taken, with Road Programming as one of the DSS.

Pinard et al [9] defined five components of a RMS based on a functional basis as follows:

1. Base Information Function Elements; e.g.: - Network Information, Traffic Information, Accident Information.
2. Evaluation Function Elements; e.g.: - Pavement Management System, Bridge Management System, Traffic Signs Management System.
3. Control Function Elements; e.g.: Cost Management System, Plant & Equipment Management System.
4. Road Charging Function Elements; e.g.: Road Use Pricing System.

5. Execution Function elements; e.g.: Maintenance Management System.

Lyinam et al [11] defines "*the pavement management system (PMS)*" as a set of tools or methods which provides important information to decision makers in finding cost effective strategies for supplying, assessing, appraisal and maintaining pavements in a serviceable condition. The objective of a PMS is to achieve the best value and uses of the available public funds in the same time insuring road safety, environmental protection, economic development and transportation efficiency. The PMS is consisted of two basic components:

- A comprehensive database, which contains current and historical information on pavement present condition, pavement structure, and traffic.
- A set of tools which allow to determine existing and future pavement conditions at the same time predict financial needs, and identify and prioritize pavement preservation projects.

**i. Management Function in RMS**

The Transport Research laboratory[12] identifies four management functions, with each of the function carried out as a sequence of activities known as ***management cycles*** (Robinson et al, 1998) shown in the figure 2.1. Those functions are: ***Planning, Programming, Preparation*** and ***Operation***. The table 1 below indicates the application of those functions within a road administration.

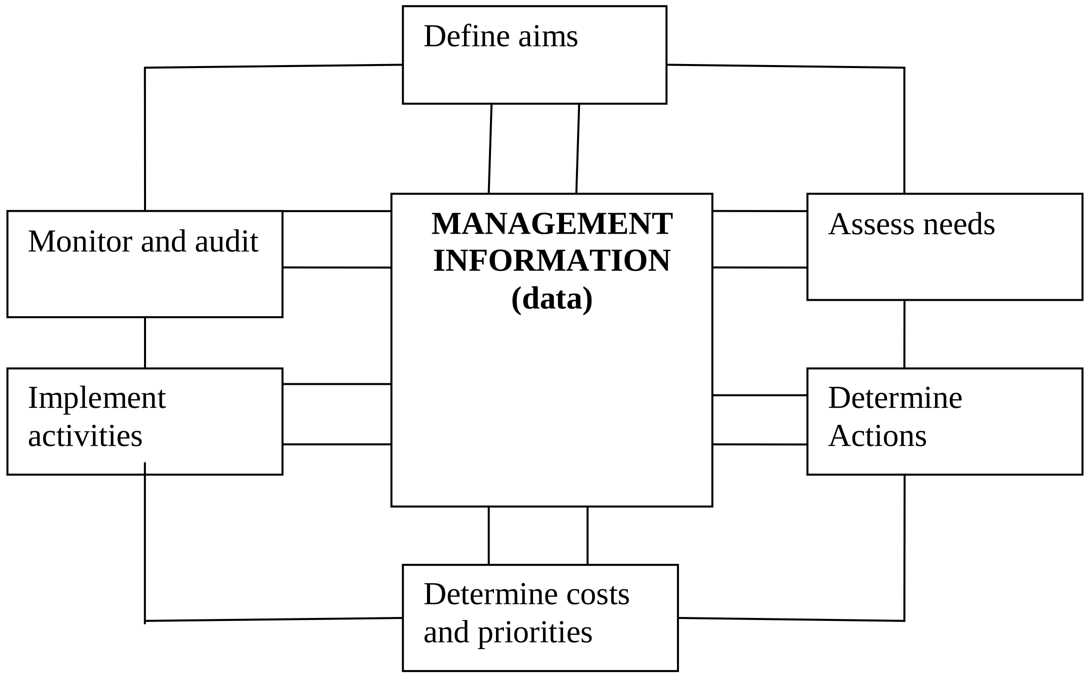
**Road Management System Functions**

Table 1 **RMS Functions**

| Function | Typical Management | Network coverage | Time horizon | Management |
|---|---|---|---|---|
| Planning | - Defining road standard which minimise cost,<br>- Determining the budget required to support defined standards | Entire Network | Long term (strategic) | Senior managers and policy makers |
| Programming | Determining the work programme that can be undertaken within the budgetary period | Sections likely to need treatment | Medium term (tactical) | Managers and budget holders |
| Preparation | - Design of works<br>- Preparation and issue of contract or work instruction | Contract or work packages | Budget year | Engineers, technical and contracts staff |
| Operation | Undertaking tasks as part of works activity | Sub-sections where works are taking place | On-going | Works supervisors |

Source: [12]

Figure 1 **Management Cycle**




Source : [12]

What involves in the management functions? According to Kerali et al. [4]; the answers are given below:

1. Planning

This involves an analysis of the road system as a whole, typically requiring the preparation of long term, or strategic, planning estimates of expenditure for road development and preservation under various budgetary and economic scenarios. Predictions may be made of expenditure under selected budget heads, and forecasts of highway conditions in terms of key indicators, under a variety of funding levels. The physical highway system is usually characterized at the planning stage by lengths of road, or percentages of the network, in various categories defined by parameters such as road class or hierarchy, traffic flow/capacity, pavement and physical condition. The results of the planning exercise are of most interest to senior policy makers in the road sector, both political and professional. Work will often be undertaken by a planning or economics unit within a road agency.

2. Programming

This involves the preparation, under budget constraints, of multi-year road works and expenditure programmes in which those sections of the network likely to require maintenance, improvement, or new construction, are identified in a tactical planning exercise. The programming activity produces estimates of expenditure, under different budget heads, for different treatment types and for different years for each road section. Budgets are typically constrained, and a key aspect of programming is to prioritize works to find the best value for money in the case of a constrained budget. Typical applications are the preparation of a budget for an annual or rolling multi-year work programme for a road network, or sub-network. Programming activities are normally undertaken by managerial-level professionals within a road agency, perhaps in a planning or a maintenance department.

3. Preparation

This is the short-term planning stage where road schemes are packaged for implementation. At this stage, designs are refined and prepared in more detail; bills of quantities and detailed costing are made, together with work instructions and contracts. Typical preparation activities are: the detailed design of an overlay scheme; the detailed design of major works, such as a junction or alignment improvement, lane addition, etc. For these activities, budgets will normally already have been approved. Preparation activities are normally undertaken by relatively junior professional staff and technicians in a technical department of a road agency, and by contracts and procurement staff.

4. Operations

These activities cover the on-going operation of a road agency. Decisions about the management of operations are made typically on a daily or weekly basis, including the scheduling of work to be carried out, monitoring in terms of labour, equipment and materials, the recording of work completed, and the use of this information for monitoring and control. Activities are normally focused on individual road sections with measurements often being made at a relatively detailed level. Operations are normally managed by sub-professional staff, including works supervisors, technicians, clerks of works, and others.

The table 2 (Kerali, 2001) below shows the changes occurred as the management process moves from *planning* through to *operations*,

**Table 2** Road Management Process

| Activity | Time horizon | Responsible Staff | Spatial coverage | Data detail | Mode of computer operation |
|---|---|---|---|---|---|
| Planning | Long term (strategic) | Senior management and policy level | Network-wide | Coarse/ summary | Automatic |
| Programming | Medium term (tactical) | Middle-level professionals | Network or sub-network | | |
| Preparation | Budget year | Junior professionals | Scheme level/ Sections | | |
| Operations | Immediate/ very short term | Technicians/ sub-professionals | Scheme level/ sub-sections | Fine/detailed | Interactive |

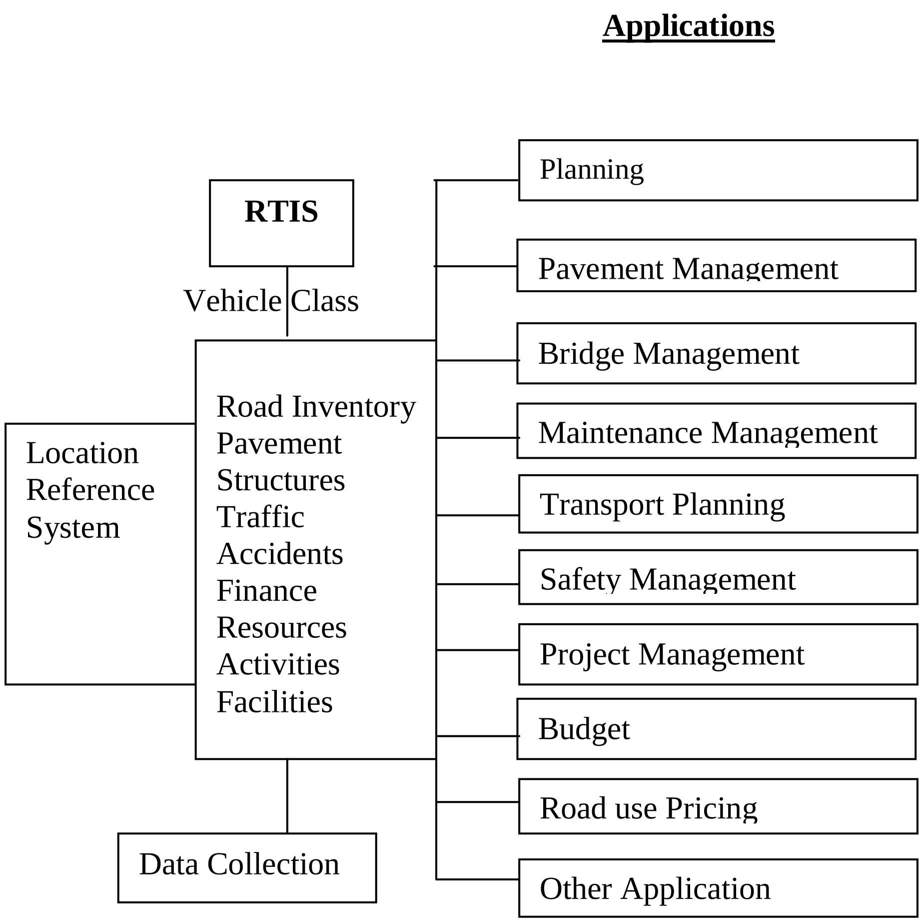
Road Programming is the preparation of works for a road network for a rolling year to make the road open and at it maximum capacity. As there are four categories of possible works (routine and periodic maintenance, special and development works); the most suitable work projects to be included in the road programming preparation, under budget constraint, need a proper and efficient method (or protocol) of selection and ranking. This work is concentrated on programming management function.

ii. **Information System**

Information is the basis of taking decisions concerning all the activities in the road sectors, as road asset requires proper planning, careful management and the provision of satisfactory services to the road users. Investment decisions need reliable, relevant, accessible and affordable information, such as traffic demand, pavement and other road asset conditions, prediction on future performance and acceptable levels of service. That information is necessary so that rational and informed judgment can be made as itis now evident that road deterioration is unavoidable and we need to choose and determine priorities between alternatives works, either new construction or maintenance of existing facilities, under funds constraint.

Paterson and Scullion [13] define the Road Information System (RIS) as *a system for identifying, collecting, storing, retrieving, and managing all data relating to road which are relevant to the planning, management and operation of a road network.* Surveying of the entire road network is necessary to get information. The figure 2 below shows different types of data relevant to the decision to be made.

Figure 2 **Data Type and their Application**. **HIS**: Highway Information System and **RTIS**: Road Transport Information System



## 1. Data Selection Criteria

Paterson and Scullion [13] have described four major criteria for data to be collected and selected for database of the RMS, which Relevance, Appropriateness, Reliability and Affordability. TRL [12] makes a summary of the signification of those criteria, which are below:

1. ***Relevance***

Every data item collected and stored must have a direct influence on the output that is required from the system. Other data items which may be considered as desirable, interesting or possibly useful in the future should be omitted in favour of those that are essential, relevant and of immediate use unless a very good cost-benefit case can be made for their collection.

2. ***Appropriateness***

The volume of data and the frequency of updating them are major determinants of the cost of operating the management system. Some types of data are collected at different times in a staged process, and the intensity and detail of measurement may differ between these stages, usually adding progressively more detail to the basic information acquired originally. For example: for pavement structural assessment as part of a strategic *planning* process, data on road condition would need broad coverage across the network, but would have a low sampling rate; however, for engineering design of a project at the later *preparation* stage, intensive sampling over the limited extent of the project would be necessary to refine the design and contract quantities. The technology and resources involved in acquiring, processing and managing the data should be appropriate to the administration's capacity for maintaining the equipment, conducting the surveys, and sustaining the data processing.

3. ***Reliability***

Data reliability is determined from the following:

- The accuracy of the data, defined by a combination of precision (the error associated with repeated measurements made at separate times or places, or by separate operators and/or instruments) and bias (the degree to which the mean measurement reflects the range and variability of all data points).

- Their spatial coverage; for network-level planning, low intensity sampling is adequate whereas, for engineering design of projects at the preparation stage, intensive sampling is needed with full coverage of the project area.
- Completeness of data is important because missing items degrade the reliability of the outcome.
- Currentness ensures that data which change rapidly from year-to-year, or which have a large impact on the ultimate decision, are kept up-to-date more than data which do not change so rapidly or are less sensitive.

A balance between the reliability of data and certainty of outcome should be sought. For example: High precision, intensive sampling of entire networks, such as can be obtained using mechanized methods, may represent over-investment if the results are only to be used for broad planning.

***4. Affordability***

The volume and quality of the data items, and the associated data acquisition, must be affordable in terms of the financial and staff resources available to collect data and keep them current. The scope and quality of data are choices that must be weighed against the resources required to sustain them in the long-term, and against the value of the management decisions that rely upon them.

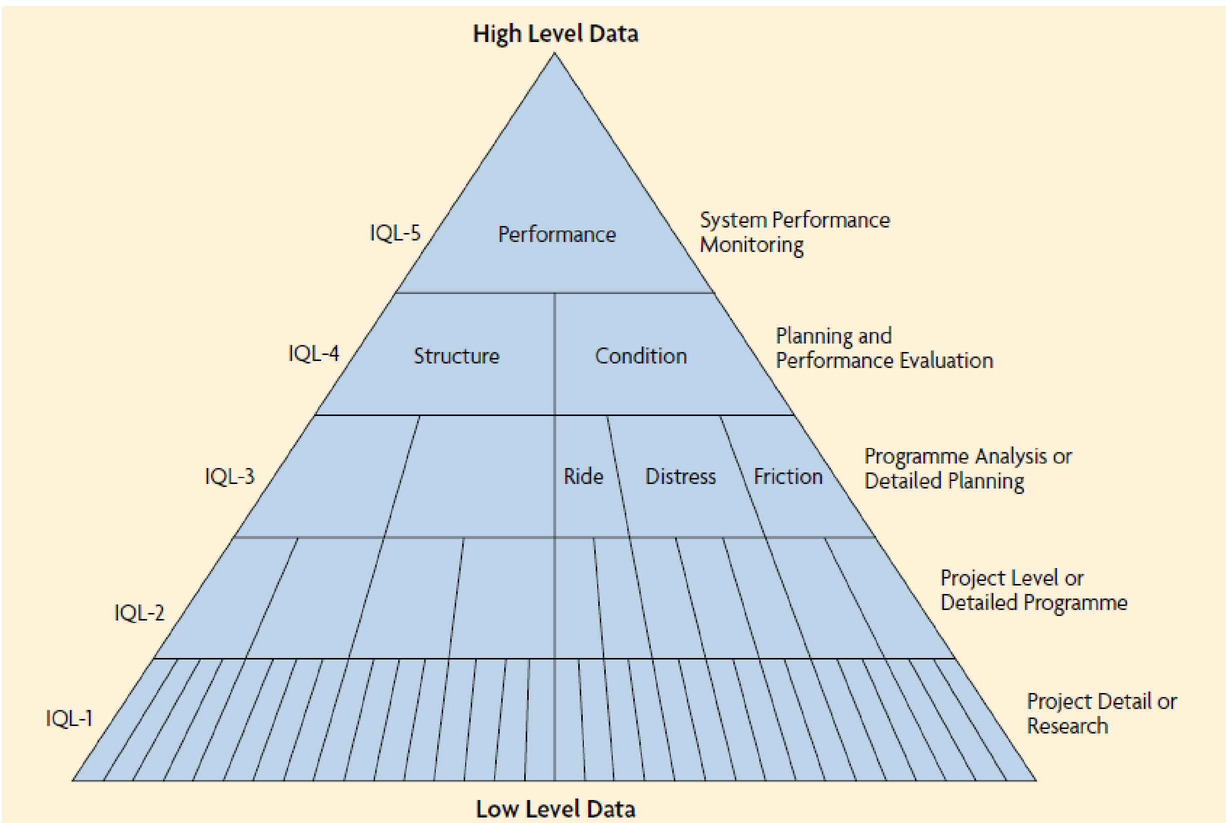
Available resources and skills vary between road administrations, and may change over time. For small organizations, or where skills and resources are scarce in a larger organization, simple and basic types of data, quality and collection methods must suffice. Where skills and resources are more abundant, a wider range of data, including the use of automatic collection methods, may be appropriate. Problems arise when administrations with very limited resources are responsible for managing large road networks.

## 2. Information Quality Levels (IQLs) and Function level

### 1. IQLs

As we are moving from different management functions (e.g.: from planning to programming or from programming to preparation or from preparation to operation), the level of data details increases. The concept '*Information Quality Level (IQL)*' introduced and recommended by the World Bank [13] has been used for the different level of data detail requirement through different management function type. The World Bank classified level of data details in five IQLs types.

Figure 3 **IQLs Types**




Source: [13]

The table 3 below shows gives types of IQLs and short description about them

**Table 3 IQLs Description .**

| Information quality level | Short description | Data collection |
|---|---|---|
| IQL-I | Most detailed and comprehensive | Short to limited lengths or isolated samples using specialised equipment, slow except for advanced automation |
| IQL-II | Detailed | Limited length using semi-automated methods, or full coverage using advanced automation at high speed |
| IQL-III | Summary details with categorisation of values | Full sample using high-speed, low accuracy semi-automated methods, or sample at slow speed, or processed from other data |
| IQL-IV | Most summary | Manual or semi-automated methods, processed or estimated |

**Source: [13]**

For example, the road condition roughness for the preparation can be expressed in term of IRI value (m/Km), while for planning and programming we can use the term good, fair and bad. The table 4 below shows the requirement of IQLs for different system type (or management function).

**Table 4** IQLs for System type

| System type | Information Quality Level |
|---|---|
| Planning | IQL-IV |
| Programming | IQL-III/IV |
| Preparation | IQL-II/III |
| Operation | IQL-I/II |

**2. Functional Level**

Paterson and Scullion [13] define five functional levels: Sectoral, network (planning and programming), project (engineering design and construction), operations (facility management) and research and development. Those levels will help to clarify the different levels at which given information is used at varying degrees of aggregation and timing. The World Bank, through Paterson and Scullion [13], has defines each of the functional levels as followed:

**i.** At the ***Sector*** **system level**, the highway system is viewed as a whole, barring perhaps some regional geographic divisions. This is the most visible level, being that viewed by government and the public in terms of budgets and statistics on extent and level of service. Major categories of information are Financial, Inventory and Utilization/Performance

**ii.** At the ***Network level,*** the planning, programming and budgeting of public works and expenditures for road development and maintenance require information on the road system as a network of links with jurisdictional, functional, traffic demand, and physical characteristics, and on the related physical resources and costs. This network-level information is used for the processes of forecasting, allocating, scheduling, spending and controlling the use of public funds on road works.

**iii.** At the ***Project level,*** the design and construction phases of the road works start to operate and information data such a specific road link or section, structure or facility are used in the technical design and evaluation of works. It is at this level to works, such new construction, maintenance or rehabilitation, will be undertaken.

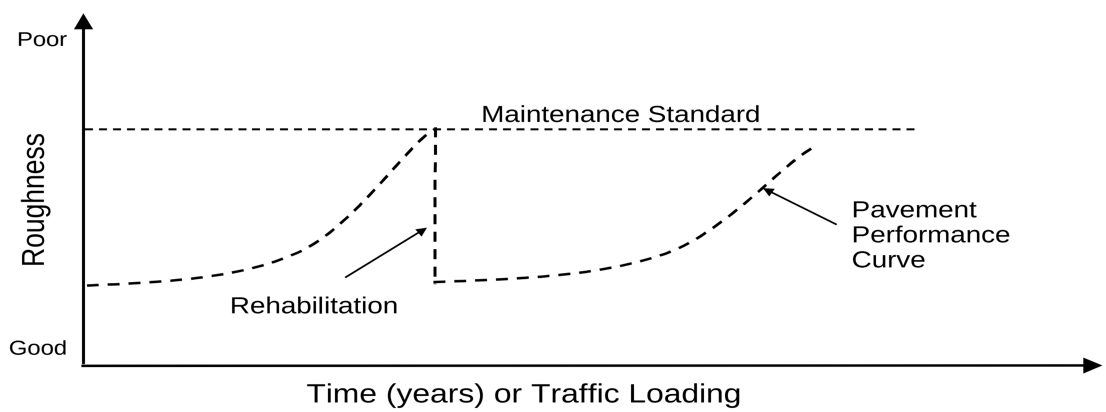
**iv.** At the ***Operational level,*** facilities and operations management operate in either real-time or very short-term time scales, operating and maintaining traffic control devices, maintaining roads and structures in functional operation through routine and emergency maintenance operations, responding to and resolving incidents such as accidents, hazardous material incidents, road blockages, etc., and (in some cases) collecting fees. -- Data items may include inventory of personnel, materials, equipment and control devices; performance or productivity indicators; disbursement and physical progress profiles; and so on.

**v.** At the ***Research and Development,*** the data needs for research are still more detailed and precise than for project-level or operations. The data are usually study-specific and may reside only on an independent data base. However, they will frequently establish coefficient or parameter values that are used in the main system, such as calibration factors, and they will be used directly in sophisticated project analysis.

### iii. Road Works

After the construction of a road, the road asset will be subjected to different factors, such as traffic loading, environmental and poor drainage effect, which will result to it deterioration. Also the pavement deterioration rate will be affected by the standards of maintenance to repair some defects on the pavement surface, such as cracking, ravelling, potholes, etc., in order to preserve the good condition of the surface pavement to continue to serve efficiently and properly (for example, surface treatments, overlays, etc.). This means that the road pavements condition directly depends on the maintenance or improvement standards applied to the road.
Figure 4 below illustrates the predicted trend in pavement performance represented by the riding quality that is often measured in terms of the international roughness index (IRI).

Figure 4 **Life-Cycle Pavement Analysis**




Source: [4]

Road works, with works meaning all the construction and maintenance activities to be carried out on a road network are divided into four categories [12] and are summarized in the table 5 below:

Table 5 **Category of road Works for RMS**

| Category | Frequency | Budget | Examples |
|---|---|---|---|
| Routine | At intervals of less than 12 months | Normally recurrent | - Cyclic maintenance<br>- Reactive maintenance |
| Periodic | At intervals of several years | Recurrent or capital | - Preventive maintenance<br>- Resurfacing<br>- Overlay<br>- Pavement reconstruction |
| Special | Cannot be estimated with certainty in advance | Special or contingency, but sometimes recurrent | - Emergency works<br>- Winter maintenance |
| Development | Planned at discrete points in time | Normally capital | - Widening<br>- Realignment<br>- New construction |

Source: [12]

Routine Maintenance Works are works that are needed to be taken each year.
Periodic Maintenance Works are works planned to be carried out regularly at interval of several year.
Special Maintenance Works are works which the frequency of cannot be estimated with certainty in advance.
Development Works are work projects planned at discrete points in time that result in improved road capacity or changes in alignment.

## 2.2. Review of MCA methods

### 2.2.1. Definition and Generalities

Barfod et al. [14] define Multi-Criteria Analysis (MCA) as an appraisal tool to identify the appropriate alternative among a multitude while different points of view which can be sometime conflicting, are considered. MCA is a technique which deals with complex and multifaceted decisions which require a number of information, a large amount of alternative outcomes and criteria to assess these outcomes [15]. DCLG [16] affirms that the role of MCA is to deal with difficulties that human decision makers had to handle a complex number of information in a consistent way.

The application of multi-criteria analysis goes back to the 1960s [5, 17], the method evolved from the operational research field. To overcome the complexity to select and prioritize in the decision making, MCA play a role of giving an interactive process where stakeholder's preferences are model in order to obtain the consensual option. It is not meant to find the best option in a decision making problem but rather to support decision-makers exploring their preferences and tolerances so as to minimize eventual post-evaluation disappointment [5, 17]; Huang et al. [18] researched and found that more than 300 papers have been published between 2000 and 2009.

MCA steps are arranging in many ways; generally when the indicators to measure objectives' achievement and all possible and feasible alternatives are identified, there are presented in a form of a " performance matrix" or a 'decision matrix' to which decisions or choices will be based. Although the number of alternatives can be allowed to reach huge values, the number of criteria should be kept reasonably low; [16, 17] suggested not exceeding eight criteria for effective analysis. Conventionally alternatives are organized per row in the decision matrix while criteria scores are arranged into columns.

### 2.2.2. MCA methods and principles

MCA techniques, which are able to deal with quantitative criteria such environmental and social benefit [19] (are used in road investment appraisal to identify rank preferred option, to make and choice a limited number of projects or to distinguish acceptable from unacceptable road projects. There exists many MCA types and DCLG [16] gives some reasons:

1. There are many different **types of decision** which fit the broad circumstances of MCA,
2. The **time** available to undertake the analysis may vary,
3. The amount or nature of **data** available to support the analysis may vary,
4. The **analytical skills** of those supporting the decision may vary, and
5. The **administrative culture and requirements** of organizations vary.

A set of objectives and measurable criteria is needed to be established, and MCA will set up preferences between options. MCA as subjective approach to decision making, need to establish also a relative *weights* for which each criterion contribute to the objectives. This will lead to the setting up of the performance matrix where each row describes an option and each column the performance of options against each criterion.

MCA's performance matrix may be seen as the final product of the analysis; with the decision makers to attribute to which extent the objectives have been met by the matrix. The intervention of *Scoring* is introduced also to reduce the subjectivity of such intuitive analysis of the decision makers.

DCLG [16] said that there exist two stages used in MCA to establish the performance matrix:

1. Scoring: the expected consequences of each option are assigned a numerical score on strength of preference scale for each option for each criterion. More preferred options score higher on the scale, and less preferred options score lower. In practice, scales extending from 0 to 100 are often used, where 0 represents a real or hypothetical least preferred option, and 100 is associated with a real or hypothetical most preferred option. All options considered in the MCA would then fall between 0 and 100.
2. Weighting: numerical weights are assigned to define, for each criterion, the relative valuations of a shift between the top and bottom of the chosen scale.

There are three methods of scoring options' performances against criteria in MCA (Manual for MCA pp42-44 (DCLG, [16]) :

- *Value function*: scores are derived from a metric whose inputs are impacts degree or any measure of achievement. It is the less subjective method once agreement of the function's nature and parameters has been reached but it is not always possible to elaborate such metrics for all criteria.

- *Direct rating*: step functions are special valuing functions where scores are allocated to alternatives by experts on basis of judgement of how they [will] perform. This approach is less preferred to the first one due to the arbitrariness that can appear. It is used when time, resource or knowledge to undertake the measurement are limited.
- *Pair-wise comparisons*: scores are indirectly deduced by computer programmes from the answers of experts to a series of pair-wise 'assessments expressing a judgment of the performance of each option relative to each of the others'. The interactive assessment framework can be structured as an Analytic Hierarchy Process (AHP) or other methods like REMBRANT or MACBETH (see manual of MCA)

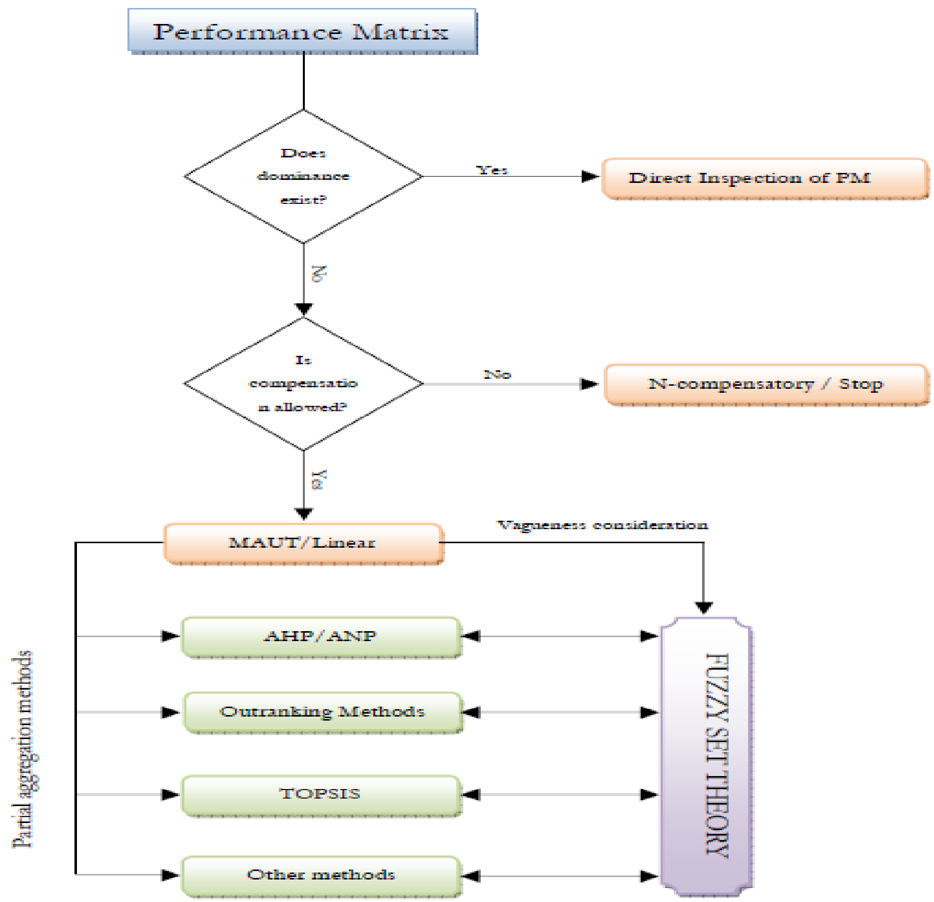
### 2.2.3. MCA types

DCLG [16] has proposed criteria to classified MCA, those are:

1. Internal consistency and logical soundness,
2. Transparency and ease of use,
3. Data requirements not consistent with the importance of the issue being considered,
4. Realistic time and manpower resource requirements for the analysis process,
5. Ability to provide an audit trail and
6. Software availability, where needed.

Also the multiplicity of MCA type can be explained by its wider application, diversity of analysis and the skill of the operator (DCLG, [16]). The figure 5 below summarizes MCA types and methods used in the transport, environmental and energy sector:

Figure 5**: MCA types and methods**




Source: [17]

Huang et al. [18], Preez and Kuyler [15], or else in the manual for MCA (DCLG, [16]) we can find a good classification of MCA. Here is a classification of MCA type in broader classes:

- **MAUT**: An example of this theory is the three stage procedure as applied by Keeney and Raiffa (1976). In this procedure, the establishment of a performance matrix is the first stage, while the second is a determination of the inter-dependence of criteria. The third stage consists of a mathematical estimation of the decision regarding the performance of an option on each of the separate criteria. Although the procedure is effective, it is considered to be relatively complex and more appropriate for implementation in major projects where time and expertise are available [15].

- **Outranking methods**: This method evaluates alternatives and use outranking to eliminate those that are dominant. All options are assessed in terms of the extent to which they exhibit sufficient outranking with respect to the full set of options being considered as measured against a pair of threshold parameters. Concerns about the outranking approach are that it is dependent on arbitrary definitions of what outranking constitutes and that threshold parameters are set and later manipulated by the decision-maker [15]. ELECTRE and PROMETHEE are the most known outranking methods.
- **AHP**: Analytic Hierarchy Process consists of pair-wise comparisons of alternatives within criteria. Although often partially applied in the whole MCA process for weight estimation it can be used for whole process if the number of pair-wise comparisons is manageable. AHP is the most popular MCA variant though it has some non-negligible drawbacks [18, 17].
- **TOPSIS**: Technique for Order Preferences by Similarity to Ideal Solution uses normalized weighted score to measure distances of each alternative from positive and negative ideal solutions. The closeness coefficient deriving from both distances is used for option ranking [18, 17].

### 2.3. **MCA Steps**

The steps of multi-criteria are [16, 17, 20]:

1. *Establishment of decision context*: elaborate objectives and make an identification of stakeholders or people who may be affected by the decision and those who are accountable for their consequences; at this stage the social and technical aspects of the analysis can be determined to know which type of MCA to use.
2. *Identification of options*: this is a brainstorming process which consists of determining feasible and realistic but not necessarily less expensive alternatives or solutions that could be undertaken to achieve the objectives; the superiority of MCA is often manifested at this step of analysis which can also be looped back from any downstream stage in addition to the possibility of identifying win-win solutions as the process goes on [21].

3. *Identification of criteria* or attributes reflecting the impact of each options on the objectives or the constraints; the key feature of criteria is measurability; furthermore, they should altogether fully capture options' overall performance without being redundant.
4. *Scoring process*: describes the expected performance of each option against criteria. It is the process by which alternatives' consequences toward objectives achievement are estimated and converted into scores that are comparable. A scale and a measurement method need to be chosen at this stage, they should be convenient and easy to use. Extreme impacts are anchored at the extreme values of the scale.
5. *Weighting process*: assigns a weight to each criterion reflecting their relative importance to the decision and the degree of tolerance to compensation among criteria when one index is to be generated by aggregation from several scores. A high variability among weights indicates that stakeholders favor some criteria than others, i.e. they won't tolerate any compensation of less favored attribute on highly favored ones [18].

   Weights are normally expressed in percentages and chosen so that their sum equals to 100%. Weights can be determined (provided) either by stakeholders or experts or estimated from analytical assessment like the AHP or entropy method.
6. *Aggregation of scores* and weights into a single index for comparison. Several methods of aggregation exist. The nuances among MCA methods arise often from this step; a thorough discussion on this topic has been done in previous sections.
7. *Examination of the results*: at this step it is relevant to verify the consistency and coherence of results.
8. *Sensitivity analysis*: the process consist in varying one or more input variables at time and assess the effect a random error could have on the output results.

### 2.4. **Taxonomy of MC**

The trust of Stakeholders and decision makers in MCA approach is reduced due to the differences in MCA taxonomy [17]. Aven [22] has criticized the use of many definitions as a hindrance to professional application and research development. Here are some short definitions of the some expressions used in MCA [17]:

*Stakeholders* are people who have any kind of investment be it financial or otherwise in the consequences of decision (to be) taken, in other word they can significantly influence or be influenced by the decision (DCLG, [16]). Stakeholders may not necessarily be directly involved in the MCA process they can chose to be represented by experts. Example of stakeholders is local authority, government or a group of people directly affected by transport activities. For instance occupants of houses next to a highway to be upgraded are subjected to exposure on an increase of air and/or noise pollution levels subsequent to the road works.

*Experts* are external people who participate in MCA to provide information relevant for the success of the analysis. It is assumed that they can -following their experience and expertise describe or predict more accurately the impact of any alternatives on either criterion. Academic and research professionals as well as senior technicians are often chosen as experts.

*Criteria* or attributes are rod measures of objective achievement; Calderon et al. [23] have defined criteria as ‘tools informing about conditions, performance of a defined process, or the attainment of a defined outcome’ (p51). Criteria can be grouped following a pre-established hierarchy so that coherent attributes are clustered into one criterion. A high degree of independency among criteria should be sought as much as possible so that they form altogether a structure similar to a vector space’s base. Depending on their measurability, criteria can be classified into two broad categories: *subjective* criteria and *objective* criteria [24, 25]. The latter refer to impacts that can be quantified in monetary terms or any other form of formalized measurement while the former include all attributes that are non/ill-defined in monetary terms and can only be suitably rated in linguistic terms i.e. words such as ‘low’, ‘very good’, etc. An example of qualitative or subjective criterion is public nuisance as considered by Chang et al. [26].

*Benefit criteria* are those for which the higher an option scores the more it is preferred while for *cost criteria* options’ scores are inversely proportional to their preferences; here preference refers to both probability and utility (DCLG, [16]) manual of MCA p61). An attribute where options have quite similar score may be given lower weight than another whose span between options’ scores is large.

*Alternatives* or options are the possible solutions that are considered for assessment.

*Decision matrix* or performance matrix or impact matrix is the table of values (often numbers3) where at the intersection of a row and a column lies a value indicating the extent to which the alternative along the row performs against the criterion mentioned in the column.

### 2.5. **Application of MCA**

MCA have been applied in many sectors such as transport investment, environmental, staff recruitment, etc. It was found that MCA variants are used in combination of 2 or 3. An MCA would for instance integrate AHP, ELECTRE and fuzzy set theory. In such combination, AHP is often used to determine criteria weights while the other variants are applied for making the aggregation of scores to derive a single index which serve as ultimate comparison factor [27, 28]. In the environmental field, Chang et al. have applied it in waste management field where stakeholders did not want a landfill in their neighbourhood. Also MCA have been applied to identify the ideal remedial solution to a contaminated site where there is a conflict interests between efficacy of attenuation method and their cost [29].

Kaya and Kahraman [30] have applied an integrated fuzzy AHP-ELECTRE methodology to help authority make suitable decision on location and prioritization of urban industrial planning in Istanbul-Turkey. Liu et al. [21] and Yang et al. [30] have coupled fuzzy and TOPSIS to solve decision problem in invasive species management and contaminated soil remedial fields, respectively. Table 2.4 shows a number of areas where MCA methods have been applied in environmental field and the MCA type used.

Here are some of applications of MCA in transport sector: Teng and Tzeng [31] have applied fuzzy multi-criteria on urban transport investment alternative; Filippo et al. [32] ranked environmental restoration options of highways; Gühnemann et al. [7] have applied MCA in the prioritization of national road infrastructure in Ireland.

Table 6 **MCA applications**

| Article | Area of application | MCA type | Criteria number | Number expert | Scale |
|---|---|---|---|---|---|
| Turkeys et al. (2009) | Green supply chain management | ANP | 6 | 11 | 7 |
| Kaya and Kahraman (2011) | EIA for urban industrial planning | | 8 | 4 | 7 |
| Chang et al. (2008) | Best location for sitting landfill | | 5 | 2 | 5 |
| Liu et al. (2010) | Invasive species risk management | | 9 | 10 | 5 |
| Yang et al. (2012) | Identification of ideal remediation solution to contaminated site | | 6 | Public and experts consultation | 5 |
| Ding (2011) | Choice of partnering shipping company | | 17 | 3 | 9 |
| Anisseh and Yusuff (2011) | Evaluation of university faculty for tenure and | | 3 | 3 | 9 |

| | | | | | |
|---|---|---|---|---|---|
| | promotion | | | | |
| Chu (2002) | Selection of plant location | | 3 | 3 | 9 |
| Wang and Lee (2007) | Evaluation of airport operation performance | | 4 | 3 | |
| Vahdani et al. (2011) | Robot and prototyping process selection | | 15 | 4 | 7 |
| Saghafian and Hejazi (2005) | University staff recruitment | | 6 | 4 | 7 |
| | | | 5 | 3 | 7 |
| Jiang et al (2011) | Group belief MCDM problem | | 4 | 3 | 4 |
| Izadildhah (2009) | Hospital staff | | 5 | N/A | 5 |
| Sun and Lin (2009) | | | 12 | 12 | 5 |
| Sii and wang (2003) | Offsboce construction selection | Delphi fuzzy | 7 | 5 | 4 |
| (Zougri and benyoucef, 2012) | Selection of supplier | Fuzzy TOPSIS | 4 | 5 | 5 |

Source: [17]

## 2.6. **Decisions Making Tools in Transport Investment**

### 2.6.1. Decision making tools and process in Transport Sector

The most common form of appraisal method used in government undertakings (or in the public sector) for decision-making is *Cost-Effectiveness Analysis (CEA)* and *Cost Benefit Analysis (CBA)*; where both techniques are monetary ways of comparing different forms of input and output by ranking them, and can be seen themselves as MCA approach (DCLG, [16]).

DCLG [16] has proposed the following process of decision making to develop a policy, programme or project:

- ***Identifying Objectives:*** The objectives should be specific, measurable, agreed, realistic and time-dependent. The Treasury Green Book has classified three objectives, those are ultimate, intermediate and immediate objectives:
    1. *Ultimate objectives* are usually framed in terms of strategic or higher-level variables, such as the level of economic growth, social cohesion or sustainable development. These objectives may be stated in White Papers, or in Departmental or Agency plans or in annual reports.
    2. *Immediate objectives* are those which can be directly linked with the outputs of the policy, programme, or project. Consideration of a proposed option needs to concentrate on those criteria which contribute to the immediate, and hence to the ultimate objectives.
- ***Identifying options for achieving the Objectives:*** Once the objectives are defined, the next stage is to identify options that may contribute to the achievement of these objectives. Potentially sensible options then need to be developed in detail. This may range from broad policy design, such as the design of tax policy, through to the more detailed design of individual investment projects. There can be an important feedback to the design stage from all the subsequent stages of appraisal/evaluation.
- ***Identifying the criteria to be used to compare the options:*** The next stage is to decide on how to compare different options' contribution to meeting the objectives. This requires the selection of criteria to reflect performance in meeting the objectives. Each criterion must be measurable, in the sense that it must be possible to assess, at least in a qualitative sense, how well a particular option is expected to perform in relation to the criterion.

- ***Analysis of the options:*** The next stage is analysis. CEA, CBA and MCA can be used to analyse.
- ***Making choices:*** he final stage of the decision making process is the actual choice of option. This needs to be seen as a separate stage because none of the techniques available, whether they be financial analysis, cost-benefit analysis, or the different forms of multi-criteria analysis, can incorporate into the formal analysis every judgement, for example about future changes in the state of the world, or income distribution, or political impact, which the ultimate decision needs to take into account.
- ***Feedback:*** Good decision making requires a continuous reassessment of choices made in the past. Individual decision makers may learn from their own mistakes, but it is important that lessons be learned in a more formal and systematic way, and communicated to others, so that they can inform future decisions.

### 2.6.2. CBA no longer appropriate

Micevičiene et al. [5] argued that CBA is 'too small-scaled' to be used in evaluation of transport projects or policies because it analyzes only monetary impacts and fails for non-monetized impacts such as environmental impacts, even if it has been used for a long-time in making decisions in the transport sector, especially in transport investment.
CBA is also criticized for its limitation to not taking into account the interactions between different impacts, expensive to collect relevant data, some impacts cannot be quantified exactly in monetary terms (such as reduction in the number of deaths, time saved, etc) and on political or philosophical ground (DCLG, [16]).

Sager and Sorensen [33] have found that faith in CBA has decreased among spokespersons and politicians. In Norway, the parliament has been responsible for decision regarding investment in transport project, however it decisions scope have gradually decreased over time with small projects being delegated to Public Road Administration. Scepticism against CBA among members of parliament (MP) has grown once they realized that its results may be manipulated by varying discount rate, they have not however removed CBA step in the evaluation process for formality purpose. Sager and Sorensen (2011) argued that sensibility of CBA performance to discount rate was generalized to other input parameters such as traffic forecast, value of time and this led to MPs discrediting the whole method i.e. the negative attitude originally held on discount rate has been extended to the entire approach [17].

CBA through discount rate can be subjected to political manipulations and thus loses its ordinary impartial nature as a selecting tool [17]. This is again illustrated by the Norway example, where contrasting opinions of political parties about CBA have swung when the discount rate has been differentiated per mode of transport. The parties to the Left who are pro-railways had for a long time been opposed to CBA approach but after the differentiation of discount rate they changed their mind; this same amendment to CBA in Norway led Right wing parties to stop promoting it, as they used to and became anti-CBA [17].

### 2.6.3. Multi-Criteria Decision Analysis.

Multi-Criteria Decision Analysis (MCDA) is the form of MCA with many application in both public and private sector. DCLG (2009) defines it as ‘’*both an approach and set of techniques which help to look at complex problems that are characterized by any mixture of monetary and non-monetary objectives and to break the problem into more manageable pieces to allow data and judgments to be brought to bear on the pieces, and then to reassemble the pieces to present a coherent overall picture to decision makers with the purpose to serve as an aid to thinking and decision making, but not to take the decision.’’*

Keeney and Raiffa [34] was the first to elaborate MCDA and it was built on decision theory which is almost associated with the decision trees, modelling of uncertainty and the expected utility rule. They accommodated multi-attributed consequences and provided a theoretically sound integration of the uncertainty associated with future consequences and the multiple objectives those consequences realize.

DCLG [16] stipulate that MCDA can be structured to:

- Show the decision maker the best way forward,
- Identify the areas of greater and lesser opportunity,
- Prioritize the options,
- Clarify the differences between the options,
- Help the key players to understand the situation better,

- Indicate the best allocation of resources to achieve the goals,
- Facilitate the generation of new and better options, improve communication between parts of the organization that are isolated, or
- Any combination of the above.

#### 2.6.3.1.Uncertainty, Risk and MCDA

Zhang et al. [35] said that uncertainty is caused by the combination of the lack of knowledge in the cause-effect relationship and the inherent imprecision in the forecast of causes and effects. Calderon et al. [23] argued that high uncertainty is often embodied in strategic transport projects due to the long-term forecast effects.

Aven [22] defines Risk as a function of initiating event, state of the system, the probability of the consequences of the event, the knowledge of the background and uncertainty not captured by probability. Aven [22] and Haimes [36] considered risk as a vector of the function of:

- Time,
- The probability of the threat (initiating event) and its specificity (input),
- The probability of the consequences, given the threat,
- The vector of the states of the system (including its performance capability, vulnerability and resilience),
- The vector of the resulting consequences,
- The vector uncertainty factors, not captured by the probabilities.

DCLG [16] agreed that it is possible to accommodate uncertainty and risk in a coherent way in MCDA due to its theoretical roots. The correct approach to accommodate uncertainty and risk is to construct a decision tree showing the options and their consequences in a form of a tree, then generate a probability-weighted score for each option which will provide a clear overall preference and ranking of the option.

#### 2.6.3.2. Steps in MCA

MCDA can be used either retrospectively to evaluate things to which resources have already been allocated, or prospectively to appraise things that are as yet only proposed (DCLG, [16]). DCLG [16] proposed the following stages in MCA when applied:

1. **Establish the decision context.**

1.1. Establish aims of the MCDA, and identify decision makers and other key players.

1.2 Design the socio-technical system for conducting the MCDA.

1.3 Consider the context of the appraisal.

2. **Identify the options to be appraised.**
3. **Identify objectives and criteria.**

3.1. Identify criteria for assessing the consequences of each option.

3.2. Organize the criteria by clustering them under high-level and lower-level objectives in a hierarchy.

4. **'Scoring'. Assess the expected performance of each option against the criteria. Then assess the value associated with the consequences of each option for each criterion.**

4.1. Describe the consequences of the options.

4.2. Score the options on the criteria.

4.3. Check the consistency of the scores on each criterion.

5. **'Weighting'. Assign weights for each of the criterion to reflect their relative importance to the decision.**
6. **Combine the weights and scores for each option to derive an overall value.**
7. **Examine the results.**
8. **Sensitivity Analysis.**

## 2.7. **Review of mathematical concepts on MCA**

### 2.7.1. The Analytical Hierarchy Process (AHP)

The AHP method was first developed in 1980 by Saaty and in 2000 Vargas upgrades its process. Theoretically the AHP is based on four axioms given by Saaty; these are:

***Axiom 1***: The decision-maker can provide paired comparisons $a_{ij}$ of two alternatives *i* and *j* corresponding to a criterion/sub-criterion on a ratio scale which is reciprocal, i.e. $a_{ji}=1/a_{ij}$.

***Axiom 2***: The decision-maker never judges one alternative to be infinitely better than another corresponding to a criterion, i.e. $a_{ij} \neq \infty$

***Axiom 3****:* The decision problem can be formulated as a hierarchy.

***Axiom 4***: All criteria/sub-criteria which have some impact on the given problem, and all the relevant alternatives, are represented in the hierarchy in one go.

### 2.7.2. Fuzzy set theory

Zadeh [37] was the first to initiate the Fuzzy set theory and Bellman and Zadeh [38] was the first to introduce the fuzzy set theory in the MCA to reduce the human subjectivity and vagueness of human language [17]. The subjectivity of the scoring of qualitative criteria is often based on the human judgement which is from an expert on the issue judgement. This subjectivity just reduces the arbitrariness of the judgement but does not eliminate it [17]. The following definitions will provide brief and clear introduction of fuzzy set theory [17]:

**Definition 1**: Let U be a universe set. A fuzzy set A of U is defined by a membership function $f(x) \rightarrow [0,1]$, where $f(x), \forall x \varepsilon U$, indicate the degree of belonging of x to A [17].

**Definition 2**: The subset A of pairs [x, f(x)] in U is called a fuzzy number if it fulfils the following properties:

• *Normality*: There exist at least one x for which $f(x) = 1$

• *Convexity*: $\forall x, y \in U, f(vx + (1 - v)y) \geq \min(f(x), f(y))$ Where $0 \leq v \leq 1$

Except otherwise indicated, fuzzy number will be denoted in this work as quadruplet $A(a_1, a_2, a_3, a_4)$ called a trapezoidal fuzzy number or triangular fuzzy number when $a_2$ is equal to $a_3$:

**Equation 1**:

$$f(x) = \begin{cases} \frac{x - a_1}{a_2 - a_1}, & a_1 \leq x < a_2 \\ 1, & a_2 \leq x \leq a_3 \\ \frac{a_4 - x}{a_4 - a_3}, & a_3 < x \leq a_4 \\ 0, & otherwise \end{cases}$$

**Definition 3**: Extension of ordinary operation to fuzzy numbers; let $A(a_1, a_2, a_3, a_4)$ and $B(b_1, b_2, b_3, b_4)$ be two fuzzy numbers. The ordinary arithmetic operations have been extended to fuzzy set theory as follows

- Addition: $A \oplus B = (a_1 + b_1, a_2 + b_2, a_3 + b_3, a_4 + b_4)$
- Subtraction: $A \ominus B = (a_1 - b_1, a_2 - b_2, a_3 - b_3, a_4 - b_4)$
- Multiplication: $A \otimes B \cong (a_1 x b_1, a_2 x b_2, a_3 x b_3, a_4 x b_4)$
- External multiplication: $A \odot r = (a_1 \times r, a_2 \times r, a_3 \times r, a_4 \times r), r \in R$

**Definition 4**: Let $A(a_1, a_2, a_3, a_4)$ and $B(b_1, b_2, b_3, b_4)$ be two fuzzy numbers, the distance d(A, B) between both objects have been defined in different ways, but we have retained the following formulation: **Equation 2**:

$$d(A,B)=\sqrt[2]{\sum_i^4 (ai - bi)^2}$$

**Definition 5** Let A be a fuzzy number, $f_A(x)$ its membership function and h(x) a function that measure the importance of the value x. Deffuzifying A is to determine the Yager index Y(A) with the following formula

**Equation 3**:

$$Y(A) = \frac{\int_0^1 h(x) fA(x) dx}{\int_0^1 fA(x) dx}$$

### 2.7.3. TOPSIS Principles

The core principle of TOPSIS is the definition of two extreme alternatives with opposite attributes. At one end there is a positive ideal solution (PIS) which is assumed to fulfill the best level for attribute considered and the negative ideal solution (NIS) with the worst attribute values [24, 39]. The use of fuzzyfied criteria scores and/or weights in TOPSIS yields fuzzy TOPSIS. If an MCA problem is assimilated to a geometric system of _ points in an O-dimensional space [40], TOPSIS approach could be understood as a process that consist of computing the Euclidian distance of each point (=alternative) to extreme 'ideal' points refer to in TOPSIS jargon as Positive Ideal Solution and Negative Ideal Solution; they are may be imaginary. When TOPSIS was first introduced in 1981 it was assumed that weights and scores are exact values however this in not often the case in real world since sometimes incomplete and no obtainable details are substituted by human judgement often based on preference and are thus vague in nature [41]. The incorporation of fuzzy theory into MCA has enabled to simultaneously work on both qualitative and quantitative data in a decision making process. Furthermore Kuchta [42] cited in (Tsao, [43]) argued that fuzzy set theory is more flexible than probability theory when risk and uncertainty are concerned.

Indeed it was found in literature that fuzzy set theory had been used for assessment of quantitative criteria whose degree of uncertainty is high. For example (Filippo et al., [32]) have evaluated the risk of accident with three quantifiable indicators such as percentage of road surface with defects and percentage of highway surface without horizontal signage; but because the probability of accident occurrence can only be determinate with limited precision from these factors they converted crisp values into first linguistic variables using inference block and Mamdami Inference Method (MIM) and second convert the latter into fuzzy numbers.

Fuzzy TOPSIS has been applied on diverse areas of decision making including:

- Evaluation of hotel quality services;
- Identification of suitable initial aircraft training to air force academy;
- Evaluation of industrial robotic system;
- Order selection and pricing of manufactures.

In this work we have chosen to use fuzzy TOPSIS as the one of the main decision supporting tool, with Fuzzy AHP another decision making tool, because it is easy to understand and straight forward to apply.

#### 2.7.4. Fussy-TOPSIS

In this research study, also the hybrid method of Fuzzy-TOPSIS was used. It is a comprehensive and easy to implement method to rate and prioritize alternatives. The ranking of this method was compared to the ranking of Fuzzy AHP. This allowed identifying the level of concordance between both methods of MCA. The application of Fuzzy TOPIS can be summarized in the following steps:

i. *Sampling*: A selection of sample roads projects, the same as selected with Fuzzy AHP, from Rwanda Road Networks was done. The qualitative scores of those selected samples must not be decimal and then convert them into fuzzy numbers.

ii. *Performance matrix*: Scores of **m** alternatives for **n** criteria are assembled in the Performance Matrix **P** where crisp values are used for quantitative criteria and fuzzy values are used for qualitative criteria.

**P=** $(Q_{ij}/Q'_{ik})$**, I = 1,…m; j=1,…l; k=l+1,…n** with

$Q_{ij}$**:** Crisp score for l quantitative criteria

$Q'_{ik}(x_{ik}, y_{ik}, z_{ik}, v_{ik})$**:** fuzzy score for (n-l) qualitative criteria.

iii. *Normalization*: Normalization is applied on performance scores to eliminate the effect of different measure units of criteria. It is also used to convert benefit and cost scores into dimensionless index [17, 25]. The performance matrix is normalized as with equations below:

N= $(r_{ij}/\check{r}_{ik})$

$$r_{ij} = \frac{s_{ij}}{\sqrt{\sum_i s_{ij}^2}}$$

$$\check{r}_{ik} = \frac{\check{s}_{ik}}{\sqrt{\sum_i v_{ij}^2}}$$

iv. *Weight*: From the normalized matrix a weighted normalized matrix U= $(u_{ij}/\bar{u}_{ik})$ where each element is obtained by multiplying the corresponding element from normalized matrix by the weight of the criteria.

v. *Defuzzyfication*: Fuzzy numbers of the weighted normalized matrix were de-fuzzyfied by employing Yager method simplified by equation below: **Equation 4**

For $\bar{u} = (a_{ik}, b_{ik}, c_{ik}, d_{ik})$

$$u_{ik} = Y(\bar{u}_{ik}) = a_{ik} + b_{ik} + c_{ik} + d_{ik} - \frac{(d_{ik}dc_{ik} - a_{ik}b_{ik})}{d_{ik} + c_{ik} - a_{ik} - b_{ik}}$$

vi. *Ideal Solutions*: Determine positive ideal solution (PIS) and negative ideal solution (NIS). The positive ideal solution is the option which yields the greatest benefits and lowest cost to the community. In the same way the negative ideal solution is the solution which has the smallest benefits and highest costs. They are determined thanks to the **equation 5** below:

PIS = $(\bar{u}_i : max\ (\bar{u}_{ij}) f\ \mathcal{E}\, B\ or\ \min(\bar{u}_{ij'}) f'\ \mathcal{E}\, C)$

NIS = $(\bar{u}_i : min\ (\bar{u}_{ij}) f\ \mathcal{E}\, B\ or\ \max(\bar{u}_{ij'}) f'\ \mathcal{E}\, C)$

B: Set of benefit criteria

C: Set of cost criteria

vii. *Hamming distances*: They are computed as Euclidian distance. The distance of alternative I from PIS, $\lambda_i$ , and the corresponding distance form NIS, $v_i$ are given by the following equations: **Equation 6**

$$\lambda_i = [\sum_{j}^{n} (u_{ij} - \bar{u}_{ij})^2]^{1/2}$$

$$v_i = [\sum_{j}^{n} (u_{ij} - \bar{u}_{ij})^2]^{1/2}$$

i. *Closeness coefficient*: The ratio of negative hamming distance to the sum of hamming distances is defined as the closeness coefficient, equation below. The latter is used to rank alternatives where those with high closeness coefficient are top ranked.

$$k_i = \frac{v_i}{\lambda_{i+} v_i}$$

The closeness coefficient does not only provide ranking between alternatives, it also give insight about their relative degree of importance [17].

### 2.7.5. Sensitivity Analysis Methods

Sensitivity analysis is the study of how the uncertainty in the output of a mathematical model or system (numerical or otherwise) can be apportioned to different sources of uncertainty in its inputs [44]. Sensitivity analysis can be useful for a range of purposes, including:

1. Testing the robustness of the results of a model or system in the presence of uncertainty.
2. Increased understanding of the relationships between input and output variables in a system or model.
3. Uncertainty reduction: identifying model inputs that cause significant uncertainty in the output and should therefore is the focus of attention if the robustness is to be increased (perhaps by further research).
4. Searching for errors in the model (by encountering unexpected relationships between inputs and outputs).
5. Model simplification – fixing model inputs that have no effect on the output, or identifying and removing redundant parts of the model structure.
6. Enhancing communication from modellers to decision makers (e.g. by making recommendations more credible, understandable, compelling or persuasive).
7. Finding regions in the space of input factors for which the model output is either maximum or minimum or meets some optimum criterion (see optimization and Monte Carlo filtering).

Sensitivity analyses can be either "local" or "global". A local analysis addresses sensitivity relative to point estimates of parameter values while a global analysis examines sensitivity with regard to the entire parameter distribution [45].

For this research study, Sensitivity Analysis is focused on the study of variability of expected performance as the criteria weights are systematically modified, in order to assess the robustness of the results. This change of the criteria weights will be done only by modifying the weights of the two more important criteria between them and modification of the other weights of more less important criteria.

Intuitively, one may think that the larger the weight for a criterion is, the more critical that criterion should be. However, this may not be the case. A criterion may be important while not critical. A critical criterion is a criterion with small change (as a percentage) in its weight may cause a significant change of the final solution.

# III. Methodology

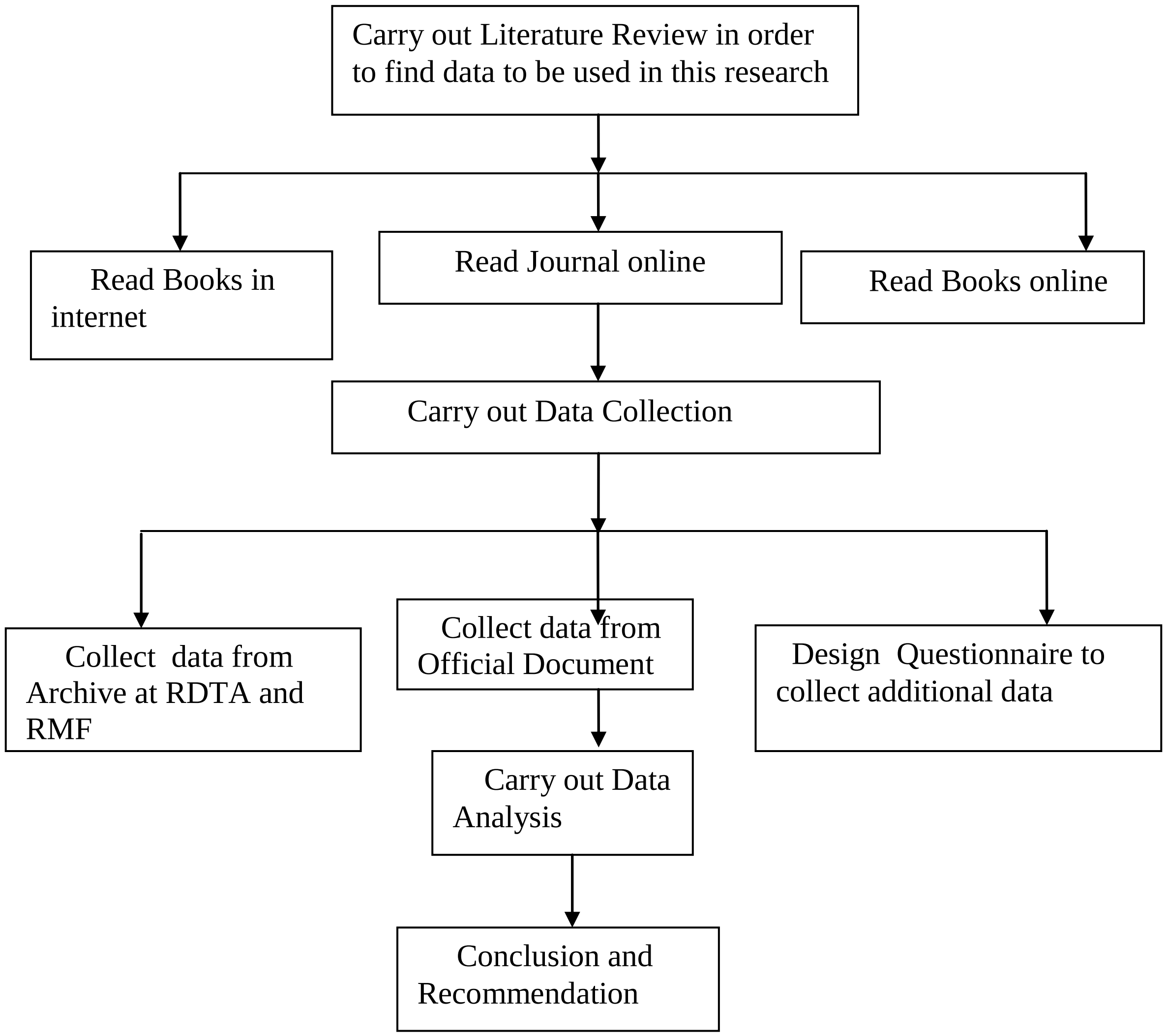
## 3.1.Introduction

This chapter describes methodologies for data collection and reduction, and for data analysis and conclusion and recommendation. The previous chapter, literature review, was the review of:

- Road Asset Management with a focus on the preparation of a road program,
- MCA methods available which lead me to identify two methods for this study: AHP and Fuzzy AHP.

The purpose of methodology is to describe how to achieve the aim and objectives of the study, which is to prepare a multi-year road works program using MCA. Several methodologies were used in this research, which included the initial discussion, literature review, data collection, data analysis and Conclusion and Recommendation as illustrated in the figure 6 below:

**Figure 6** Methodology used for this research study




### 3.2. Research Methodology

Research methodology used in this study ensures that the study was done with the right procedure in order to achieve the aim and objectives of this research study. The methodology is broken down into four stages and these stages are listed below:

1. Literature review;
2. Data collection;
3. Data analysis; and
4. Conclusion and comment

### 3.3. Literature Review

**M**ethodology used for this chapter was to read materials such as books, journals, online journals, and online websites and conference papers about MCA methods and Road Asset Management. These reading materials provided a source for secondary data which will be needed for this research and to give limitation for the entire works. From there, this data serves as a benchmark for primary data collection.

### 3.4.**Data Collection**

Data for this study has been obtained from various sources, especially from Public Institution of the Republic of Rwanda and internet through reading of different material. Other data has been from questionnaire for public servant, academic area and expert working in Rwanda in the transport sector. Data required for this research study can be divided into two types, ***Primary and Secondary Data.***

#### 3.4.1. Primary data

The collection of primary data for this study will be obtained through two methods:

**i. Questionnaires**

A questionnaire has been drawn up and distributed to experts working in transportation section in public institution, academic area and private sector. The required data need from the questionnaires is the criteria and sub-criteria to be used in this study. A questionnaire has been drawn up and distributed to the target personnel or experts to obtain the required data.

In this study, 13 of questionnaires were distributed to those who are involved in road works as in public institution (8), academic level (3) and private sector (2) in Rwanda, with the purpose to make a protocol of prioritization of road works.

The designed criteria and Sub-Criteria (between brackets) are **ECONOMIC DEVELOPMENT** (job creation, increase productivity and facilitate exports with neighbouring country), **TRANSPORTATION EFFICIENCY** (ADT and Road Condition), **ENVIRONMENTAL PROTECTION** (reduction of negative environmental impact) and **ROAD SAFETY** (reduction of annual accident number). Economic Development and Environmental protection criteria are qualitative while Transport Efficiency and Road Safety criteria are quantitative.

The table 7 below shows the criteria used and their acronym:

**Table 7** Criteria and Sub-Criteria acronym

| Criteria | Acronym |
|---|---|
| Economic Development | ED |
| Transportation Efficiency | TE |
| Road Safety | RS |
| Environmental Protection | EP |
| Job creation | JC |
| Facilitate Expert and Import | FEI |
| Increase Productivity | IP |
| Traffic | TR |
| International Roughness Index | IRI |

Those criteria and their respective sub-criteria were identified through the objectives of Rwanda policies, such as Vision 2020, EDPRS 2, Public Transport Policy and Strategy for Rwanda, and Rwanda Strategic Transport Master Plan, and through the experience of other countries I have read in the internet, especially in the practices used in United State of America.

Here is the definition of three primary criteria:

1. Wikipedia defines Economic Development (**ED**) as the continuous and determined effort of policy makers and communities that promotes the quantitative and qualitative changes in the economy of a region through development of human capital[1].
2. According the Organization for Economic Co-operation and Development (OECD), Environmental protection refers to any activity to protect, maintain or restore the quality of environmental media through preventing the emission of pollutants or reducing the presence of polluting substances in environmental media, whether on individual, organizational or global (international) level. It may consist of: changes in characteristics of goods and services, changes in consumption patterns, changes in production techniques, treatment or disposal of residuals in separate environmental protection facilities, recycling, and prevention of degradation of the landscape and ecosystems[2].

[1] http://http://en.wikipedia.org/wiki/Economic_development access on 17th June 2014
[2] https://stats.oecd.org/glossary/detail.asp?ID=836 access on 23th November 2013

3. According to Wikipedia, **Road traffic safety** refers to methods and measures for reducing the risk of a person using the road network being killed or seriously injured. The users of a road include pedestrians, cyclists, motorists, their passengers, and passengers of on-road public transport, mainly buses and trams. Best-practice road safety strategies focus upon the prevention of serious injury and death crashes in spite of human fallibility (which is contrasted with the old road safety paradigm of simply reducing crashes assuming road user compliance with traffic regulations)[3].

The results or data from the questionnaires were used to evaluate and rank different conflicting alternatives using weights of the criteria and the scores given by different experts. This main purpose is to minimize the subjectivity of MCA methods by using the expert point of view and question asked were focused on matters related to the main objective, to preparation three year maintenance and rehabilitation road works program using Rwanda Paved Road Network.

Aggregation of data from criteria weights and score of different alternatives was done by calculating the arithmetic mean of the data from questionnaire of our 13 experts. For the evaluation and ranking of criteria and sub-criteria, we used questionnaire data from 10 experts and for the evaluation and ranking of alternatives, we used only 3 experts.

**ii. Archive**

Archives data was the data obtained from Rwanda Transport Development Agency [46], and those data are for the road condition, specifically International Roughness Index (IRI) for the National Paved for the fiscal year 2011-2012. The whole Rwandan National Paved Network composed of 16 paved roads classified, of which 3 roads are under rehabilitation, in our research study we used only 10 paved roads and they were selected randomly.

### 3.4.2. Secondary data

Secondary data was obtained through literature, references such as books, journals, conference papers, magazines, newspapers, reports, internet surfing and so on. And the chapter two was about this, where two MCA methods was selected to be used for the data analysis.

[3] http://en.wikipedia.org/wiki/Road_safety access on 23th November 2013

## 3.5. Data analysis

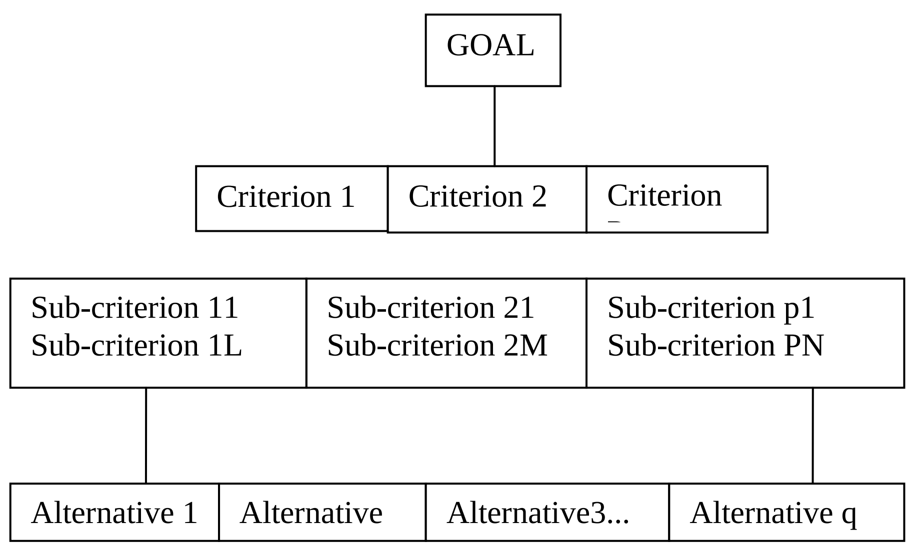
In this research for the data analysis two methods will be used: AHP and Fussy AHP S to rank the criteria and make a priority protocol for different road works. Then the sensitivity analysis will be done and the estimate of budget for the prioritize road sections to prepare the road work program for each year.

### 3.5.1. AHP

AHP decomposes a problem into a hierarchy of sub-problems which can easily be evaluated and those evaluation are converted into numerical values for the ranking of each alternative on a numerical scale. Here are the steps for AHP methodology:

***Step 1***: The problem is decomposed into a hierarchy of goal, criteria, sub-criteria and alternatives.

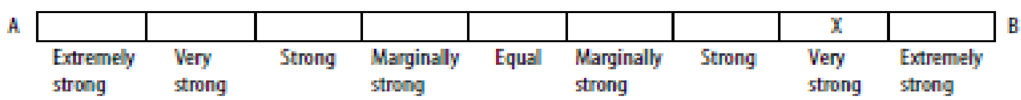
Figure 7 **Generic Hierarchic Structure**




Source: [47]

A hierarchy is similar to an inverted tree structure and is more orderly form of a network. Saaty suggests that a useful way to structure the hierarchy is to work down from the goal as far as one can and then work up from the alternatives until the levels of the two processes are linked in such a way as to make comparisons possible. At the root of the hierarchy is the goal or objective of the problem being studied and analyzed. The leaf nodes are the alternatives to be compared. In between these two levels are various criteria and sub-criteria. It is important to note that when comparing elements at each level a decision-maker has just to compare with respect to the contribution of the lower-level elements to the upper-level one.

***Step 2***: Data are collected from experts or decision-makers corresponding to the hierarchic structure, in the pair-wise comparison of alternatives on a qualitative scale as described below. Experts can rate the comparison as equal, marginally strong, strong, very strong, and extremely strong. The opinion can be collected in a specially designed format as shown in the figure 7 below format of pair-wise comparison




***Step 3***: The pair wise comparisons of various criteria generated at step 2 are organized into a square matrix. The diagonal elements of the matrix are 1. The criterion in the *i*th row is better than criterion in the *j*th column if the value of element (*i*, *j*) is more than 1; otherwise the criterion in the *j*th column is better than that in the *i*th row. The (*j*, *i*) element of the matrix is the reciprocal of the (*i*, *j*) element.

***Step 4***: The principal eigenvalue and the corresponding normalized right eigenvector of the comparison matrix give the relative importance of the various criteria being compared. The elements of the normalized eigenvector are termed weights with respect to the criteria or sub-criteria and ratings with respect to the alternatives.

***Step 5***: The consistency of the matrix of order *n* is evaluated. Comparisons made by this method are subjective and the AHP tolerates inconsistency through the amount of redundancy in the approach. If this consistency index fails to reach a required level then answers to comparisons may be re-examined. The consistency index, CI, is calculated as

$CI = (\alpha_{max} - n)/(n - 1)$ where $\alpha_{max}$ is the maximum eigenvalue of the judgement matrix. This CI can be compared with that of a random matrix, RI. The ratio derived, CI/RI, is termed the consistency ratio, CR. Saaty suggests the value of CR should be less than 0.1.

***Step 6***: The rating of each alternative is multiplied by the weights of the sub-criteria and aggregated to get local ratings with respect to each criterion. The local ratings are then multiplied by the weights of the criteria and aggregated to get global ratings.

The AHP produces weight values for each alternative based on the judged importance of one alternative over another with respect to a common criterion.

### 3.5.2. Fuzzy AHP

The first step in AHP is to structure the hierarchy and then create pairwise comparison matrices. This is done by making 13 experts to answer a series of question in the questionnaires, see in the form in the appendix 2…

The fuzzy AHP technique is an advanced analytical method developed from the traditional AHP combined with the fuzzy set theory. Generally, in this method the decision makers' uncertainty will be reflected through crisp values. Therefore, FAHP is proposed to relieve the uncertainness of AHP method, where the fuzzy comparisons ratios are used.

To attain the priorities in FAHP, there exists many method [48]: The fuzzy least square method, method based on the fuzzy modification of the LLSM, geometric mean method, the direct fuzzification of the method of Csutora and Buckley, synthetic extend analysis, Mikhailov's fuzzy preference programming and two-stage logarithmic programming are some of these methods. For this research the geometric mean method has been used.

For the establishment of weights for criteria, theirs answers have been codified on fuzzy scale, as shown in the table 8 below:

**Table 8** Triangular Fuzzy Scale

| How important is A relative to B | Triangular Fuzzy Scale | Fuzzy number |
|---|---|---|
| Equally important | (1,1,1) | $1^{-}$ |
| Weakly important | (1,2,3) | $3^{-}$ |
| Strongly more important | (3,4,5) | $5^{-}$ |
| Very Strongly more important | (5,6,7) | $7^{-}$ |
| Absolutely more important | (7,8,9) | $9^{-}$ |

From here, the pairwise comparison matrices will be deducted with the number of row equal to column, both equal to ½*n*(n-1), with n number of criteria. For our case we have four criteria and we will have matrix of four rows and columns.

The second step is to calculate the relative weights and judgments consistency. The matrix obtained for the preview step was used to derive relative weights of criteria and sub-criteria using Eigenvector method. For the pairwise comparison matrix A, Eigen values (l) are obtained after solving the equation determinant (A-l*I) = 0. And furthermore, by solving the matrix equation (A-$l_{max}$*I)* W = 0, the relative weight vector (Eigen Vector) is calculated. In addition, the value of inconsistency for each pairwise comparison matrix obtained was calculated as followed:

$I.R = \frac{I.I}{I.I.R}$ and $I.I = \frac{Imax - n}{n-1}$ with

I.R: Rate of Inconsistency (Value of inconsistency),

I.I.: Inconsistency index,

I.R.R.: Inconsistency index for random matrix,

N: number of criteria or sub-criteria being compared one pairwise comparison matrix.

The last step is about the rating approach in Fuzzy AHP and synthesizing the relative weights to obtain final weights. Because the number of alternatives was high, 43 alternatives, we will do a sample and Microsoft Excel will be used to calculate the final weight for each criterion, where the weight of each criterion is divided by the largest sub-criteria weight among the same group and the multiplied by the weight of the corresponding criterion. The sum of the final weight is used as the priority index for each section.

### 3.5.3. Sensitivity analysis

Sensitivity Analysis is the study of variability of expected performance as the input parameters (criteria weights) are systematically modified, in order to assess the robustness of the results. The modification of input parameters, which can be either individually or combination, provides a means for examining the extent of the vagueness and disagreements between people to the final overall result.

The inputs to change are the weight of the criteria. Intuitively, one may think that the larger the weight for a criterion is, the more critical that criterion should be. However, this may not be the case. A criterion may be important while not critical. A critical criterion is a criterion with small change (as a percentage) in its weight may cause a significant change of the final solution.

In this study, a sensitivity analysis for each appraisal method, AHP and Fuzzy AHP, to assess the robustness of the final overall results by modifying the scores and weights of criteria to analyze the impact of the disagreement between experts and decisions makers in order to assess the robustness of the model made both by AHP and Fuzzy AHP; this will lead us to know the important and critical criteria.

# IV. DATA COLLECTIONAND DESCRIPTION

## 4.1.Rwanda National Paved Road Network

The national road network of Rwanda is composed of 2,837 Km of classified road with 1,171 Km of paved road and 1,667 Km of unpaved road see Appendix 1[49].This research work is focused on the maintenance and rehabilitation works on Rwandan National Paved Road Network (RNPRN) only. This paved road network is composed by 15 paved roads classified with 3 roads under rehabilitation.

### 4.1.1. Traffic data Survey

In 2010 a traffic count for paved road in Rwanda was done by a technical assistance and the table 4.1 below show the average road traffic and the number of section for each paved road.

**Table 9** Rwanda Paved Road Network

| **Road ID** | Section Number | ADT |
|---|---|---|
| RN 1 | 5 | 1595 |
| RN 2 (Under Rehabilitation) | 4 | 1362 |
| RN 3 | 8 | 1471 |
| RN 4 (4 sections are under rehabilitation) | 8 | 1504 |
| RN 5 | 4 | 653 |
| RN 6 | 5 | 478 |
| RN 7 | 5 | 366 |
| RN 8 | 2 | 718 |
| RN 9 | 2 | 460 |
| RN 10 | 1 | 87 |
| RN 11 | 3 | 260 |
| RN 12 | 1 | 146 |
| RN 13 | 1 | 518 |
| RN 14 (Under Rehabilitation) | 1 | 211 |
| RN 15 | 4 | 832 |
| RN 18b | 1 | 578 |

**Source: [49]**

This traffic survey on paved road was done by dividing classified paved road in small homogenous sections as shown in the table above. But as in Rwanda, maintenance of road is not done following the road sections but the condition of the classified road through his entire length, this research propose to use classified paved road as different alternatives to be evaluated and ranked according the selected criteria.

### 4.1.2. Road Condition Data

The road condition survey for the fiscal year 2013-2014 showed that 95 % of paved roads in Rwanda were in good condition [49] as shown in the table below.

**Table 10** Road Condition of Rwanda Road Network

| Nº | Description | Total length (Km) | Length inspected (Km) | Length in good condition | % of road in good condition |
|---|---|---|---|---|---|
| 1 | National paved road | 1,171.64 | 1,069.1 | 1,022.06 | 95.60 |
| 2 | National unpaved roads | 1,687.5 | 1,530.02 | 621.19 | 40.60 |
| 3 | All national roads | 2,859.57 | 2,599.12 | 1,643.25 | 63.22 |
| 4 | District classified unpaved road | 1,838.45 | 1,838.45 | 681.33 | 37.06 |

**Source: [49]**

The road condition is measured by measuring the international roughness index (IRI) by Rwanda Transport Development Agency. The road condition survey covers the entire road network for paved and unpaved road. In order, a paved road section to be classified in good condition, it should have an average IRI less than 4 m/Km. The table below show the road condition for all the paved road network and the average daily traffic:

**Table 11**Traffic data and Road Condition of Rwanda Road Network

| Road ID | Section Number | ADT | Road Condition (IRI in m/Km) |
|---|---|---|---|
| RN 1 | 5 | 1595 | 1.27 |
| RN 2 (Under Rehabilitation) | 4 | 1362 | |
| RN 3 | 8 | 1471 | 2.17 |
| RN 4 (4 sections are under rehabilitation) | 8 | 1504 | 1.49 |
| RN 5 | 4 | 653 | 3.61 |
| RN 6 | 5 | 478 | 3.53 |
| RN 7 | 5 | 366 | 2.24 |
| RN 8 | 2 | 718 | 3.13 |
| RN 9 | 2 | 460 | |
| RN 10 | 1 | 87 | 2.17 |
| RN 11 | 3 | 260 | 2.21 |
| RN 12 | 1 | 146 | 2.08 |
| RN 13 | 1 | 518 | 3.23 |
| RN 14 (Under Rehabilitation) | 1 | 211 | |
| RN 15 | 4 | 832 | 1.36 |
| RN 18b | 1 | 578 | 4.4 |

For this research study three paved roads, RN 12, RN 13 and RN 18b, were removed as alternatives to be evaluated and ranked. This was done in order to ease the prioritization using the two selected MCA methods: AHP and Fuzzy AHP.

## 4.2.RMF expenditures

The aim of the Economic Development and Poverty Reduction Strategy(EDPRS I from 2007 to 2012) aims was to improve transport links nationally and regionally [46], with the main focus to improve road condition of the existing paved and unpaved classified roads and the upgrading of unpaved road to paved road which will be used as regional corridor. With EDPRS II [49], the main focus is to maintain and upgrade the feeder road condition to link those national and regional paved road. It is with this regards it is proposed to make a three year as to maintain the existing road condition of the paved road network.

We have selected 10 paved sections, ranging from 34 Km to 167 Km for this study. Those alternatives will be compared and ranking using the selected following criteria the transportation efficiency, the economic development, the road safety and the national and local environmental equilibrium.

The objective of this study is to prepare a prioritization protocol for three year maintenance road works of 10 paved roads for Rwanda paved road maintenance using AHP and Fuzzy AHP as Multi-Criteria Analysis. This will be done by listing the most suitable road section for investment to be maintained for three consecutive years with the limited resources available. The table 12 below showed the expenditure of resources committed for paved road in Rwanda since 2008 given by Road Maintenance Fund (RMF).

Table 12 **Rwanda Paved Road Maintenance Expenditure**

| **Budget year** | **Routine maintenance (RWF)** | **Recurrent maintenance (RWF)** | **Periodic maintenance (RWF)** | **Study & supervision (RWF)** | **Total (in million RWF)** |
|---|---|---|---|---|---|
| **2008** | 231,223,000 | 171,516,000 | 2,157,568,000 | 61,084,000 | **2,621.391** |
| **Jan 2009 - June 2009** | 92,312,000 | 296,545,000 | 502,152,000 | 35,916,000 | **926.925** |
| **July 2009 - June 2010** | 46,338,000 | 944,708,000 | 1,722,560,000 | 534,054,000 | **3,247.660** |
| **July 2010 - June 2011** | 369,743,000 | 915,908,000 | 4,256,148,000 | 644,313,000 | **6,186.112** |
| **July 2011 - June 2012** | 49,215,000 | 5,088,724,000 | 5,525,217,000 | 956,813,000 | **11,619.969** |
| **July 2012 – June 2013** | 356,245,717 | 3,190,053,795 | 7,402,928,488 | 315,776,139 | **11,265.004** |
| **TOTAL** | | | | | **35,867.39** |

Source: [49]

The table 12 above that from the budget year 2008-2009 and 2009-2010, the resource allocated for the maintenance for paved road were around 3.5 billion of Rwandan Francs. The next fiscal year 2010-2011, the allocated resource almost doubled and reached almost 6.5 billion. The last three year, 2011-2012, 2012-2013 and 2013-2014, the allocated resource was around 6.5 billion. In this research the annually allocated resource for each year in the paved road works program will be estimated to be 6.5billion as also this is the budget allocated for the paved road network in this fiscal year 2014-2015.

One of the shortcomings of MCA as stated above is that generally decision-makers require measures for value of money as well [7], for this reason we will do cost estimate for each year road works program. The type of maintenance done is routine maintenance, recurrent maintenance, periodic maintenance and emergency works. From the table below, we can see the unit cost in Rwandan Franc/ US dollar (rate 1 USD=685 Rfw) for different works per km from this fiscal year:

**Table 13** Unit Cost for Road Maintenance works

| | Routine Maintenance | Recurrent Maintenance | Periodic Maintenance |
|---|---|---|---|
| Unit Cost in RwF | **405,000** | **11,475,662.90** | **37,250,000** |
| Unit Cost in US | **591.24** | **16,752.79** | **54,379.56** |

**Source: [49]**

It can be argued that this study has been done at Network level, because of the lack of data for some criteria and thus necessity to work with high uncertainty. The network level requires coarse data, such IRI estimate for road section and this is under IQL III/IV.

As we have 10 road alternatives in our Paved Road Network, to be evaluated and ranked according to the four criteria selected, we need a proper and clear method of prioritization of those sections works. The types of works we have are: Routine Maintenance (RoM), Recurrent Maintenance (ReM) and Periodic Maintenance (PeM).

Routine Maintenance is required continuously and it includes the vegetation control and repair and patching of potholes (PP) as the main works for paved road; while recurrent maintenance is required at the intervals during the year and includes crack sealing (CS) and edge repairs(ER). Periodic maintenance is required at the intervals of several years and includes resealing, regravelling (RG) and overlay (OV) as main work for paved road.

As we have the traffic and the road condition for each road section, the table 14 below shows an example of maintenance solution catalogue using HDM-4 model:

**Table 14** Road Maintenance works based on Traffic and Road Condition data

| Total Bituminous Network (2lane equivalent length, Km) | | | | | | | |
|---|---|---|---|---|---|---|---|
| Traffic Range (Vehicle/day) | Road Condition Range (Roughness, IRI) | | | | | | |
| | < 2 | 2 to 3 | 3 to 4 | 4 to 5 | 5 to 6 | 6 to 8 | >= 8 |
| 1 to 200 | RoM | RoM | ReM | ReM | ReM | | |
| 201 to 500 | RoM | RoM | ReM | PeM | PeM | Reconstruction | Reconstruction |
| 501 to 1000 | ReM | ReM | ReM | PeM | PeM | Reconstruction | |
| 1001 to 2000 | ReM | ReM | PeM | PeM | PeM | | |
| 2001 to 4000 | ReM | PeM | PeM | PeM | PeM | PeM | Reconstruction |
| 4000 to 6000 | ReM | PeM | PeM | PeM | PeM | PeM | |

**4.3. Data Sampling**

First of all, a statistical analysis of the distribution of scores in all criteria groups was done before converting them into linguistic variable and then we apply AHP and Fuzzy AHP on the select project. In the analysis of score all the 10 road projects were used. Secondly, in the application of AHP and Fuzzy AHP, we will do the sensitivity analysis samples of the ten projects by changing the criteria weight randomly.

The table 15 below shows the sample sizes for different tasks:

| Task | Sample size |
|---|---|
| Analysis of score | 10 projects |
| Application of Fuzzy AHP and Fuzzy TOPSIS | 10 projects |
| Sensitivity Analysis | 10 projects |
| Cost Estimates | 10 projects |

The table 16 below is the sample of road section with ADT and IRI with the proposed maintenance work following the above table:

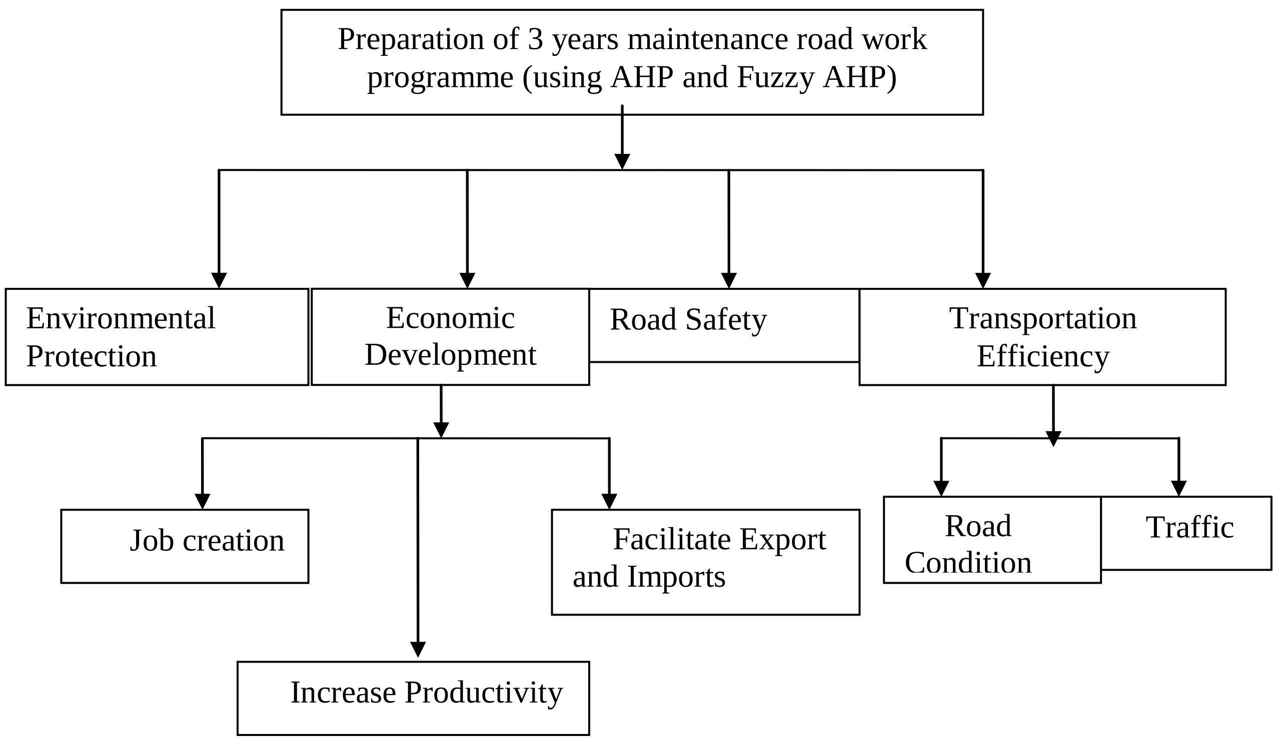
| **Road Sect** | **ADT** | **IRI** | **Maintenance Works** |
|---|---|---|---|
| RN 1 S 01 | 2,386 | 1.33 | ReM |
| RN 1 S 02 | 1,368 | 1 | ReM |
| RN 1 S 03 | 1,097 | 1 | ReM |
| RN 3 S 03 | 1,506 | 1.48 | ReM |
| RN 3 S 07 | 387 | 3.17 | PeM |
| RN 6 S 01 | 628 | 3.49 | PeM |
| RN 7 S 01 | 729 | 1.65 | ReM |
| RN 7 S 03 | 248 | 2.6 | RoM |
| RN 7 S 05 | 315 | 2.69 | ReM |
| RN 15 S 04 | 164 | 1.27 | ReM |

# V. DATA ANALYSIS AND INTERPRETATION

## 5.1.Hierarchy Structure of the Main Goal

The main goal for this research study is the preparation of 3 years maintenance road work programme and the first step is to break it in level according the criteria we have This will leads us to have a hierarchy structure of how the analysis will be done. For my research, the objective is to prepare a multi-year road works program using MCA, with the multi-year meaning 3 years and road works is only maintenance road works. Thus we have say that the objective is Preparation of 3 years maintenance road works using MCA. The MCA methods using in this research is AHP and Fuzzy AHP, and the figure 7 below illustrate the hierarchy structure of my research:

**Figure 8** Proposed 3 years Maintenance Road Works Hierarchy Structure




From the figure 8 above, we can see that we have three levels; the first is the objective of my research. The second level is the criteria used to make a protocol of prioritization of maintenance road works for the three fiscal years for the coming years. The last level is the sub-criteria of each selected criteria.

## 5.2. AHP Process and Ranking of alternatives

### 5.2.1. AHP Performance Matrix

Ten questionnaires were sent to experts involved in road works as followed: height (8) questionnaire for public institution experts, three (3) for academic area and (2) for private sector experts. The method used aggregation of each expert to obtain the weight of the criteria and their sub-criteria is the arithmetic mean, because of the fact that the respondents have similar experience, between 4-8 years of experience.

Table 17 for preference weight values for different level of importance for AHP model is shown below:

| Importance/ weights | Definition |
|---|---|
| 1 | equal |
| 3 | Weakly important |
| 5 | Strongly more important |
| 7 | very strongly more important |
| 9 | absolutely more important |
| 2,4,6,8 | Intermediate values between the two adjacent judgments |

Using the importance the importance weight performance matrix can be formed and the table 18 below show the performance matrix for the criteria of one of the expert:

| | **ED** | **TE** | **RS** | **EV** |
|---|---|---|---|---|
| **ED** | 1.00 | 5.00 | 5.00 | 5.00 |
| **TE** | 0.20 | 1.00 | 1.00 | 5.00 |
| **RS** | 0.20 | 1.00 | 1.00 | 3.00 |
| **EV** | 0.20 | 0.20 | 0.33 | 1.00 |

The maximum value of the Eigen vector for above matrix, $\lambda_{max}$=4.06 and the consistency index C.I= ($\lambda_{max}$-n)(n-1)= 0.02 with n being the number of criteria. According to the randomly generated consistency index for different size of matrix calculated by Professor Saaty (1980) and given in the table 19 below:

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| R.I | 0 | 0 | 0.58 | 0.91 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

The R.I for this research is equal to 0.91 and the consistency Ratio, C.R= C.I/R.I = 0.022 which less than 0.1 and this can be acceptable. Then the calculation of the weight matrix was and the normalization as well which gave us the following normalized weight N (0.5896, 0.1893, 0.1563, 0.0674).

The table 20 below show the performance matrix for the sub-criteria of Economic development criteria of the same expert:

| | **JC** | **IP** | **FE&I** |
|---|---|---|---|
| **JC** | 1.00 | 1.00 | 3.00 |
| **IP** | 1.00 | 1.00 | 1.00 |
| **FE&I** | 0.33 | 1.00 | 1.00 |

The maximum value of the Eigen vector for above matrix, $\lambda_{max}$=3.00 and the consistency index C.I= ($\lambda_{max}$-n)(n-1)= 0.002 with n being the number of sub-criteria. According to the randomly generated consistency index for different size of matrix calculated by Professor Saaty (1980) and given in the table 21 below:

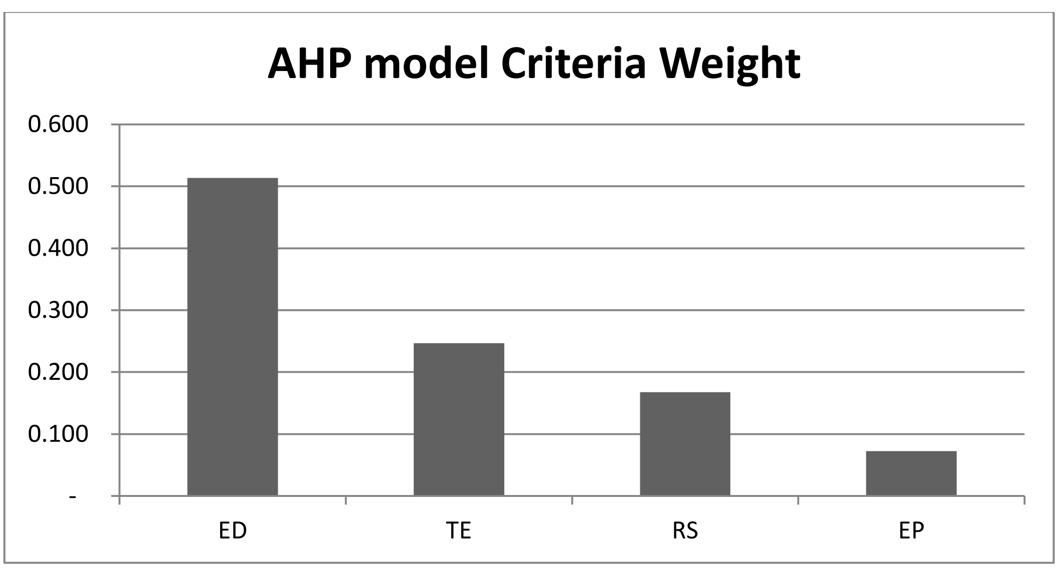
| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| R.I | 0 | 0 | 0.58 | 0.91 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

The R.I for this research is equal to 0.58 and the consistency Ratio, C.R= C.I/R.I = 0.004 which less than 0.1 and this can be acceptable. The rest of the results for all the experts for the criteria and sub-criteria performance matrix showed that the consistency ratio is less than 0.01.

The weights of the criteria represent the ratio of how much more important one criterion is than another, with respect to the goal or criterion at a higher level and the table 22 below shows the normalized weights obtained from each expert for the criteria and the aggregation result:

| **Criterion** | **Ex1** | **Ex2** | **Ex3** | **Ex4** | **Ex5** | **Ex6** | **Ex7** | **Ex8** | **Ex9** | **Ex10** | **Aggregate** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ED** | 0.58 | 0.410 | 0.590 | 0.590 | 0.510 | 0.566 | 0.338 | 0.551 | 0.482 | 0.511 | **0.513** |
| **TE** | 0.19 | 0.317 | 0.189 | 0.189 | 0.242 | 0.209 | 0.302 | 0.270 | 0.282 | 0.269 | **0.247** |
| **RS** | 0.16 | 0.180 | 0.154 | 0.154 | 0.193 | 0.131 | 0.243 | 0.115 | 0.176 | 0.165 | **0.168** |
| **EP** | 0.05 | 0.093 | 0.067 | 0.067 | 0.055 | 0.095 | 0.116 | 0.064 | 0.060 | 0.055 | **0.073** |

The weight of each success criteria is depicted in figure 8 below showing that the more important criteria proffered by the expert is the economic development annual demand
has higher priority than the other criteria as the weight is equal to 0.513; the second preferred is the Transportation Efficiency (TE) as they weighted it 0.247 and the third is the Road safety (RS) with the weight of 0.168 and the last is Environmental Protection (EP) with the weight of 0.073.



The tables 23 below show the normalized weights obtained from each expert for the sub-criteria of economic development and transportation efficiency:

| **Criterion** | **Ex1** | **Ex2** | **Ex3** | **Ex4** | **Ex5** | **Ex6** | **Ex7** | **Ex8** | **Ex9** | **Ex10** | **Aggregate** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **JC** | 0.69 | 0.597 | 0.454 | 0.454 | 0.587 | 0.580 | 0.455 | 0.597 | 0.454 | 0.574 | **0.545** |
| **IP** | 0.23 | 0.282 | 0.321 | 0.321 | 0.332 | 0.306 | 0.455 | 0.282 | 0.321 | 0.286 | **0.314** |
| **FEI** | 0.07 | 0.120 | 0.225 | 0.225 | 0.081 | 0.114 | 0.091 | 0.120 | 0.225 | 0.140 | **0.141** |

| **Criterion** | **Ex1** | **Ex2** | **Ex3** | **Ex4** | **Ex5** | **Ex6** | **Ex7** | **Ex8** | **Ex9** | **Ex10** | **Aggregate** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **TR** | 0.75 | 0.500 | 0.833 | 0.792 | 0.750 | 0.750 | 0.833 | 0.750 | 0.500 | 0.750 | ***0.721*** |
| **IRI** | 0.25 | 0.500 | 0.167 | 0.208 | 0.250 | 0.250 | 0.167 | 0.250 | 0.500 | 0.250 | ***0.279*** |

From the table 23, we can see that the weight of the sub-criteria of the economic development it is the Job Creation (JC) which is the most preferred as it was weighted 0.545; the second is the Increase of Productivity (IP) with the weight of 0.314 and the last is Facilitate Export and import (FEI) with the weight of 0.141.

From the last table, we can see that the weight of the sub-criteria of the economic development it is the traffic volume (TR) which is the most preferred as it was weighted 0.721 and the last is road condition expressed in International Roughness Index (IRI) with the weight of 0.279.

### 5.2.2. Alternatives Ranking

Three questionnaires was send to experts involved in road works and only expert involved in the programming of works in public institution was selected to making pairwise comparison matrice. The method used aggregation of each expert to obtain the weight of alternatives with respect each criterion is the arithmetic mean, because of the fact that the respondents have similar experience, between 4-8 years of experience. The table 24 below show the weights of alternatives with respect the economic development criteria of one of the expert:

| | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 1 | 1.00 | 3.00 | 3.00 | 3.00 | 1.00 | 5.00 | 3.00 | 1.00 | 3.00 | 5.00 |
| RN 3 | 0.33 | 1.00 | 1.00 | 5.00 | 5.00 | 5.00 | 1.00 | 5.00 | 5.00 | 7.00 |
| RN 4 | 0.33 | 1.00 | 1.00 | 5.00 | 7.00 | 7.00 | 1.00 | 7.00 | 1.00 | 7.00 |
| RN 5 | 0.33 | 0.20 | 0.20 | 1.00 | 1.00 | 3.00 | 3.00 | 1.00 | 3.00 | 3.00 |
| RN 6 | 1.00 | 0.20 | 0.14 | 1.00 | 1.00 | 5.00 | 3.00 | 1.00 | 5.00 | 5.00 |
| RN 7 | 0.20 | 0.20 | 0.14 | 0.33 | 0.20 | 1.00 | 3.00 | 3.00 | 1.00 | 5.00 |
| RN 8 | 0.33 | 1.00 | 1.00 | 0.33 | 0.33 | 0.33 | 1.00 | 5.00 | 3.00 | 5.00 |
| RN 10 | 1.00 | 0.20 | 0.14 | 1.00 | 1.00 | 0.33 | 0.20 | 1.00 | 5.00 | 5.00 |
| RN 11 | 0.33 | 0.20 | 1.00 | 0.33 | 0.20 | 1.00 | 0.33 | 0.20 | 1.00 | 3.00 |
| RN 15 | 0.20 | 0.14 | 0.14 | 0.33 | 0.20 | 0.20 | 0.20 | 0.20 | 0.33 | 1.00 |

The maximum value of the Eigen vector for above matrix, $\lambda_{max}$=10.036 and the consistency index C.I= ($\lambda_{max}$-n)(n-1)= -0.012 with n being the number of alternatives. According to the randomly generated consistency index for different size of matrix calculated by Professor Saaty (1980) and given in the table 25 below:

| N | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
|---|---|---|---|---|---|---|---|---|---|---|
| R.I | 0 | 0 | 0.58 | 0.91 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

The R.I for this research is equal to 1.49 and the consistency Ratio, C.R= C.I/R.I = -0.008 which less than 0.1 and this can be acceptable.  Then the calculation of the weight matrix was and the normalization as well which gave us the following normalized weight N (0.187, 0.170, 0.183, 0.075, 0.106, 0.061, 0.087, 0.072, 0.042, 0.017).

The same process was done for this expert to calculate the scores of alternatives respect to the other criteria and it was found that the results was acceptable as all their consistency ratio is less than 0.01. The normalized alternative weight with respect all the criteria for this expert are shown in the table 26 below:

| **Expert 1** | **ED** | **TE** | **RS** | **EP** |
|---|---|---|---|---|
| RN 1 | 0.1865 | 0.2408 | 0.1867 | 0.1904 |
| RN 3 | 0.1701 | 0.1439 | 0.2359 | 0.1710 |
| RN 4 | 0.1827 | 0.1489 | 0.1481 | 0.1875 |
| RN 5 | 0.0751 | 0.0582 | 0.0619 | 0.0797 |
| RN 6 | 0.1063 | 0.0927 | 0.0842 | 0.0896 |
| RN 7 | 0.0612 | 0.0779 | 0.0592 | 0.0837 |
| RN 8 | 0.0872 | 0.0449 | 0.0633 | 0.0434 |
| RN 10 | 0.0718 | 0.0704 | 0.0491 | 0.0588 |
| RN 11 | 0.0421 | 0.0561 | 0.0561 | 0.0437 |
| RN 15 | 0.0171 | 0.0662 | 0.0555 | 0.0522 |

In order to obtain the scores of the alternatives and make a ranking of priority we have to make the sum of the multiplication of the values of the above weight with the weights of respective criteria. The table 27 below gives us the scores of alternatives and their respective ranking:

The ranking is done from the highest score which is rank first to the lowest score which is ranked the last. Meaning with a budget constraint we have to select projects according to this ranking up to complete the available budget and the other remaining project will serve as priority to the next fiscal year.

## 5.3.Fuzzy AHP Process and Ranking of alternatives

### 5.3.1. Fuzzy AHP Performance Matrix

As for the AHP method, we used also ten questionnaires and they were sent to experts involved in road works as followed height (8) in public institution, three (3) in academic area and (2) in private sector. The method used aggregation of each expert to obtain the weight of the criteria and their sub-criteria is the arithmetic mean, because of the fact that the respondents have similar experience, between 4-8 years of experience.

Table 28 for preference weight values for different level of importance for fuzzy AHP model is shown below:

| Linguistic scale | Triangular fuzzy scale | Fuzzy Number |
|---|---|---|
| Equal | (1,1,1) | $1^{-}$ |
| Weakly important | (1,2,3) | $3^{-}$ |
| Strongly more important | (3,4, 5) | $5^{-}$ |
| very strongly more important | (5,6,7) | $7^{-}$ |
| absolutely more important | (7,8,9) | $9^{-}$ |

The table 29 below show the performance matrix for the criteria of one of the expert:

| | **ED** | **TE** | **RS** | **EV** |
|---|---|---|---|---|
| **ED** | (1,1,1) | (3,4,5) | (3,4,5) | (3,4,5) |
| **TE** | (0.2,0.25,0.33) | (1,1,1) | (1,1,1) | (3,4,5) |
| **RS** | (0.2,0.25,0.33) | (1,1,1) | (1,1,1) | (1,2,3) |
| **EV** | (0.2,0.25,0.33) | (0.2,0.25,0.33) | (0.33,0.5,1) | (1,1,1) |

By transforming this comparison matrix into AHP comparison matrix, we have to calculate the average for each fuzzy number and the table 30 below is the corresponding matrix:

| | **ED** | **TE** | **RS** | **EV** |
|---|---|---|---|---|
| **ED** | 1 | 4 | 4 | 4 |
| **TE** | 0.26 | 1 | 1 | 4 |
| **RS** | 0.26 | 1 | 1 | 2 |
| **EV** | 0.26 | 0.26 | 0.61 | 1 |

The maximum value of the Eigen vector for above matrix, $\lambda_{max}$=4.03 and the consistency index C.I= ($\lambda_{max}$-n)(n-1)= 0.009 with n being the number of criteria. According to the randomly generated consistency index for different size of matrix calculated by Professor Saaty (1980) and given in the table 31 below:

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| n | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| R.I | 0 | 0 | 0.58 | 0.91 | 1.12 | 1.24 | 1.32 | 1.41 | 1.45 | 1.49 |

The R.I for this research is equal to 0.91 and the consistency Ratio, C.R= C.I/R.I = 0.0097 which less than 0.1 and this can be acceptable.

Then the geometric mean of fuzzy comparison values of each criterion is calculated by using the geometric mean of fuzzy comparison values equation. The tables 32 below show the results of the geometric mean of criteria and sub-criteria:

**Criteria geometric mean and Normalized weight**

| Criteria | Geometric mean | | | Relative Fuzzy Weight | Normalized Weight |
|---|---|---|---|---|---|
| ED | 2.280 | 2.828 | 3.344 | ***0.5781*** | ***0.552*** |
| TE | 0.880 | 1.000 | 1.133 | ***0.2046*** | ***0.195*** |
| RS | 0.669 | 0.841 | 1.000 | ***0.1719*** | ***0.164*** |
| EP | 0.340 | 0.420 | 0.577 | ***0.0924*** | ***0.088*** |
| Total | 4.168 | 5.090 | 6.054 | ***1.047*** | ***1.000*** |
| Reverse | 0.240 | 0.196 | 0.165 | | |
| Increase Order | 0.165 | 0.196 | 0.240 | | |

**Economic Development Sub-criteria geometric mean and Normalized weight**

| Sub-Criteria | Geometric mean | | | Relative Fuzzy Weight | Normalized Weight |
|---|---|---|---|---|---|
| JC | 1.000 | 1.260 | 1.442 | ***0.4128*** | ***0.4047*** |
| IP | 1.000 | 1.000 | 1.000 | ***0.3297*** | ***0.3232*** |
| FEI | 0.693 | 0.794 | 1.000 | ***0.2775*** | ***0.2720*** |
| Total | 2.693 | 3.054 | 3.442 | ***1.0202*** | ***1.0000*** |
| Reverse | 0.371 | 0.327 | 0.291 | | |
| Increase Order | 0.291 | 0.327 | 0.371 | | |

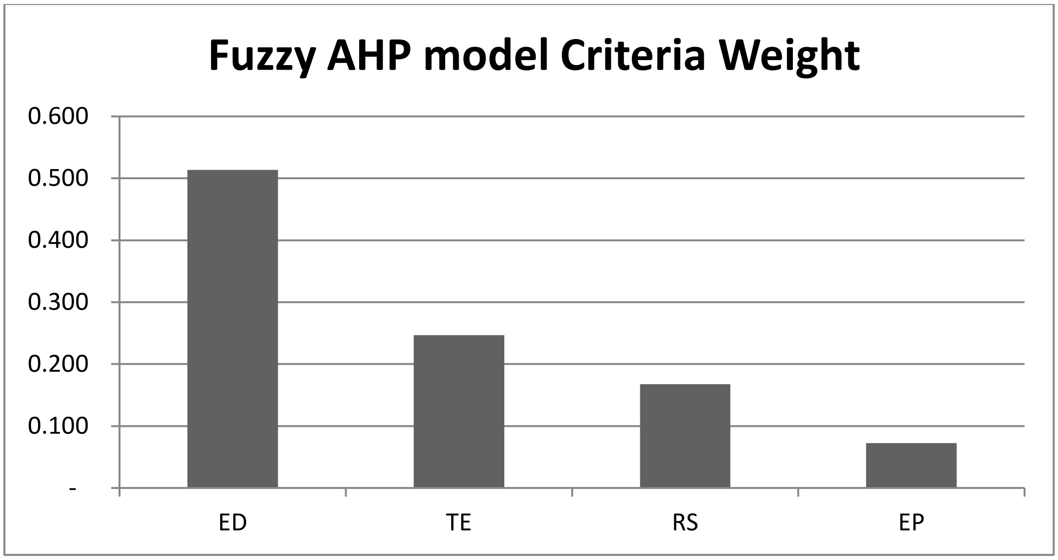
**Transportation Efficiency Sub-criteria geometric mean and Normalized weight**

| Sub-Criteria | Geometric mean | | | Relative Fuzzy Weight | Normalized Weight |
|---|---|---|---|---|---|
| TR | 1.732 | 2.000 | 2.236 | ***0.8139*** | ***0.7964*** |
| IRI | 0.447 | 0.500 | 0.577 | ***0.2079*** | ***0.2035*** |
| Total | 2.179 | 2.500 | 2.813 | ***1.0219*** | ***1.0000*** |
| Reverse | 0.459 | 0.400 | 0.355 | | |
| Increase Order | 0.355 | 0.400 | 0.459 | | |

The results for all the experts for the criteria and sub-criteria performance matrix the consistency ratio are less than 0.01. The weights of the criteria represent the ratio of how much more important one criterion is than another, with respect to the goal or criterion at a higher level and the table 33 below shows the normalized weights obtained from each expert for the criteria and the aggregation result:

| **Criterion** | **Ex1** | **Ex2** | **Ex3** | **Ex4** | **Ex5** | **Ex6** | **Ex7** | **Ex8** | **Ex9** | **Ex10** | **Aggregate** |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **ED** | 0.60 | 0.435 | 0.552 | 0.552 | 0.463 | 0.522 | 0.322 | 0.521 | 0.404 | 0.484 | **0.486** |
| **TE** | 0.17 | 0.264 | 0.195 | 0.196 | 0.234 | 0.203 | 0.276 | 0.263 | 0.3 | 0.224 | **0.233** |
| **RS** | 0.158 | 0.19 | 0.164 | 0.164 | 0.239 | 0.134 | 0.285 | 0.139 | 0.223 | 0.226 | **0.192** |
| **EP** | 0.058 | 0.111 | 0.088 | 0.088 | 0.064 | 0.141 | 0.117 | 0.077 | 0.073 | 0.066 | **0.088** |

The weight of each success criteria is depicted in figure below showing that the more important criteria proffered by the expert is the economic development annual demand
has higher priority than the other criteria as the weight is equal to 0.486; the second preferred is the Transportation Efficiency (TE) as they weighted it 0.233 and the third is the Road safety (RS) with the weight of 0.192 and the last is Environmental Protection (EP) with the weight of 0.088.




The tables 34 below show the normalized weights obtained from each expert for the sub-criteria of economic development and transportation efficiency:

| Criterion | Ex1 | Ex2 | Ex3 | Ex4 | Ex5 | Ex6 | Ex7 | Ex8 | Ex9 | Ex10 | Aggregate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **JC** | 0.677 | 0.562 | 0.208 | 0.404 | 0.514 | 0.563 | 0.442 | 0.562 | 0.404 | 0.469 | **0.481** |
| **IP** | 0.238 | 0.284 | 0.651 | 0.323 | 0.394 | 0.284 | 0.442 | 0.284 | 0.323 | 0.316 | **0.354** |
| **FEI** | 0.083 | 0.152 | 0.140 | 0.272 | 0.091 | 0.152 | 0.114 | 0.152 | 0.272 | 0.214 | **0.164** |

| Criterion | Ex1 | Ex2 | Ex3 | Ex4 | Ex5 | Ex6 | Ex7 | Ex8 | Ex9 | Ex10 | Aggregate |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **TR** | 0.643 | 0.500 | 0.888 | 0.796 | 0.644 | 0.644 | 0.797 | 0.644 | 0.500 | 0.643 | **0.670** |
| **IRI** | 0.356 | 0.500 | 0.111 | 0.203 | 0.356 | 0.356 | 0.204 | 0.356 | 0.500 | 0.356 | **0.329** |

From table 34.a, we can see that the weight of the sub-criteria of the economic development it is the Job Creation (JC) which is the most preferred as it was weighted 0.481; the second is the

Increase of Productivity (IP) with the weight of 0.354 and the last is Facilitate Export and import (FEI) with the weight of 0.164.

From the table 34.b we can see that the weight of the sub-criteria of the economic development it is the traffic volume (TR) which is the most preferred as it was weighted 0.670 and the last is road condition expressed in International Roughness Index (IRI) with the weight of 0.329.

### 5.3.2. Alternatives Ranking

Three questionnaires was send to experts involved in road works and only expert involved in the programming of works in public institution was selected to making pairwise comparison matrice. The method used aggregation of each expert to obtain the weight of alternatives with respect each criterion is the arithmetic mean, because of the fact that the respondents have similar experience, between 4-8 years of experience. Following the same procedure we did for the performance matrix, we can get the weight of the alternatives and the table 35 below shows the Normalized non-fuzzy relative weights of alternative for each criterionresults:

| | ***ED*** | ***TE*** | ***RS*** | ***EP*** |
|---|---|---|---|---|
| RN 1 | 0.1053 | 0.1111 | 0.1102 | 0.1042 |
| RN 3 | 0.1086 | 0.1088 | 0.1113 | 0.1052 |
| RN 4 | 0.1062 | 0.1091 | 0.1078 | 0.1083 |
| RN 5 | 0.1004 | 0.1009 | 0.0983 | 0.1003 |
| RN 6 | 0.1002 | 0.1010 | 0.1008 | 0.1006 |
| RN 7 | 0.0985 | 0.0978 | 0.0961 | 0.1000 |
| RN 8 | 0.0989 | 0.0977 | 0.0965 | 0.0971 |
| RN 10 | 0.0967 | 0.0926 | 0.0936 | 0.0953 |
| RN 11 | 0.0943 | 0.0910 | 0.0927 | 0.0941 |
| RN 15 | 0.0909 | 0.0901 | 0.0926 | 0.0931 |

The same process was done for this expert to calculate the scores of alternatives respect to the other criteria and it was found that the results was acceptable as all their consistency ratio is less than 0.01. The normalized alternative weight with respect all the criteria for this expert are shown in the table below:

In order to obtain the scores of the alternatives and make a ranking of priority we have to make the sum of the multiplication of the values of the above weight with the weights of respective criteria. The table 36 below gives us the scores of alternatives and their respective ranking:

| **Criteria** | | **scores of Alternatives with respect to related Criterion** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **weights** | **RN 1** | **RN 3** | **RN 4** | **RN 5** | **RN 6** | **RN 7** | **RN 8** | **RN 10** | **RN 11** | **RN 15** |
| **ED** | 0.486 | 0.105 | 0.109 | 0.106 | 0.100 | 0.100 | 0.098 | 0.099 | 0.097 | 0.094 | 0.091 |
| **TE** | 0.233 | 0.111 | 0.109 | 0.109 | 0.101 | 0.101 | 0.098 | 0.098 | 0.093 | 0.091 | 0.090 |
| **RS** | 0.192 | 0.110 | 0.111 | 0.108 | 0.098 | 0.101 | 0.096 | 0.096 | 0.094 | 0.093 | 0.093 |
| **EP** | 0.088 | 0.104 | 0.105 | 0.108 | 0.100 | 0.101 | 0.100 | 0.097 | 0.095 | 0.094 | 0.093 |
| **Score** | | 0.107 | 0.109 | 0.107 | 0.100 | 0.101 | 0.098 | 0.098 | 0.095 | 0.093 | 0.091 |
| **Ranking** | | **2** | **1** | **3** | **5** | **4** | **7** | **6** | **8** | **9** | **10** |

The ranking is done from the highest score which is rank first to the lowest score which is ranked the last. Meaning with a budget constraint we have to select projects according to this ranking up to complete the available budget and the other remaining project will serve as priority to the next fiscal year.

## 5.4.**Sensitivity analysis**

In this research study, a sensitivity Analysis was carried out to assess the robustness of the ranking results as they were systematically little changes in the criteria weights. The modification of criteria weight provides a means for examining the extent of the vagueness and disagreements between people to the final ranking overall result using either AHP or Fuzzy AHP method.

Intuitively, one may think that the larger the weight for a criterion is, the more critical that criterion should be. However, this may not be the case. A criterion may be important while not critical. A critical criterion is a criterion with small change (as a percentage) in its weight may cause a significant change of the final solution.

Sensitivity testing initially focused on particular areas:

- Ranking Sensitivity to changes of the weights of the two important criteria, economic development and transportation efficiency, the change in weight is five percent,
- Ranking Sensitivity to changes of the weights of the two other criteria, road safety and environmental protection, the change in weight is five percent.

### 5.4.1. AHP Sensitivity analysis

The tables 39 below show the change in ranking when we increase by 5 % the economic development criterion and reduce by 5 % the transportation efficiency criterion:

| **Criteria** | | **Alternatives** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **weights** | **RN 1** | **RN 3** | **RN 4** | **RN 5** | **RN 6** | **RN 7** | **RN 8** | **RN 10** | **RN 11** | **RN 15** |
| **ED** | 0.563 | 0.199 | 0.201 | 0.154 | 0.092 | 0.095 | 0.063 | 0.068 | 0.055 | 0.042 | 0.032 |
| **TE** | 0.197 | 0.248 | 0.183 | 0.184 | 0.067 | 0.072 | 0.059 | 0.054 | 0.046 | 0.043 | 0.044 |
| **RS** | 0.168 | 0.214 | 0.238 | 0.154 | 0.074 | 0.082 | 0.053 | 0.051 | 0.045 | 0.046 | 0.042 |
| **EP** | 0.073 | 0.168 | 0.167 | 0.196 | 0.097 | 0.084 | 0.078 | 0.058 | 0.055 | 0.050 | 0.048 |
| **Scores** | | 0.209 | 0.201 | 0.163 | 0.084 | 0.087 | 0.0616 | 0.0619 | 0.051 | 0.043 | 0.037 |
| **Ranking** | | **2** | **1** | **3** | **5** | **4** | **7** | **6** | **8** | **9** | **10** |
| **Initial Ranking** | | **1** | **2** | **3** | **5** | **4** | **6** | **7** | **8** | **9** | **10** |

When we increase the economic development by 5%, the ranking of alternatives changes.. From the table 39 above, we can observe that the first choice in the initial ranking become the second choice and the second choice in the initial ranking become the first choice. Also this happens for the fifth and sixth choice. For this table we can say that the economic development criterion is not only the important criterion but also the critical criterion.

The tables 40 below show the change in ranking when we increase by 5 % the economic development criterion and reduce by 5 % the transportation efficiency criterion:

| **Criteria** | | **Alternatives** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **weights** | **RN 1** | **RN 3** | **RN 4** | **RN 5** | **RN 6** | **RN 7** | **RN 8** | **RN 10** | **RN 11** | **RN 15** |
| **ED** | 0.463 | 0.199 | 0.201 | 0.154 | 0.092 | 0.095 | 0.063 | 0.068 | 0.055 | 0.042 | 0.032 |
| **TE** | 0.297 | 0.248 | 0.183 | 0.184 | 0.067 | 0.072 | 0.059 | 0.054 | 0.046 | 0.043 | 0.044 |
| **RS** | 0.168 | 0.214 | 0.238 | 0.154 | 0.074 | 0.082 | 0.053 | 0.051 | 0.045 | 0.046 | 0.042 |
| **EP** | 0.073 | 0.168 | 0.167 | 0.196 | 0.097 | 0.084 | 0.078 | 0.058 | 0.055 | 0.050 | 0.048 |
| **Scores** | | 0.214 | 0.199 | 0.166 | 0.082 | 0.085 | 0.061 | 0.060 | 0.051 | 0.043 | 0.038 |
| **Ranking** | | **1** | **2** | **3** | **5** | **4** | **6** | **7** | **8** | **9** | **10** |
| **Initial R** | | **1** | **2** | **3** | **5** | **4** | **6** | **7** | **8** | **9** | **10** |

When we increase the transportation efficiency criterion by 5%, the ranking of alternatives do not change. From the table 40 above, above we can say that the transportation efficiency criterion is not the critical criterion.

The tables 41 below show the change in ranking when we increase by 5 % the road safety criterion and reduce by 5 % the environmental protection criterion:

| **Criteria** | | **Alternatives** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **weights** | **RN 1** | **RN 3** | **RN 4** | **RN 5** | **RN 6** | **RN 7** | **RN 8** | **RN 10** | **RN 11** | **RN 15** |
| **ED** | 0.513 | 0.199 | 0.201 | 0.154 | 0.092 | 0.095 | 0.063 | 0.068 | 0.055 | 0.042 | 0.032 |
| **TE** | 0.247 | 0.248 | 0.183 | 0.184 | 0.067 | 0.072 | 0.059 | 0.054 | 0.046 | 0.043 | 0.044 |
| **RS** | 0.218 | 0.214 | 0.238 | 0.154 | 0.074 | 0.082 | 0.053 | 0.051 | 0.045 | 0.046 | 0.042 |
| **EP** | 0.023 | 0.168 | 0.167 | 0.196 | 0.097 | 0.084 | 0.078 | 0.058 | 0.055 | 0.050 | 0.048 |
| **Scores** | | 0.214 | 0.204 | 0.162 | 0.082 | 0.086 | 0.060 | 0.061 | 0.051 | 0.043 | 0.038 |
| **Ranking** | | **1** | **2** | **3** | **5** | **4** | **7** | **6** | **8** | **9** | **10** |
| **Initial Ranking** | | **1** | **2** | **3** | **5** | **4** | **6** | **7** | **8** | **9** | **10** |

When we increase the road safety criterion by 5%, the ranking of alternatives changes. From the table 41 above, we can observe that the sixth choice in the initial ranking become the seventh choice and the seventh choice in the initial ranking become the sixth choice. From the table we can say that the road safety criterion is also a critical criterion.

The tables 42 below show the change in ranking when we increase by 5 % the environmental protection criterion and reduce by 5 % the road safety criterion:

| **Criteria** | | **Alternatives** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **weights** | **RN 1** | **RN 3** | **RN 4** | **RN 5** | **RN 6** | **RN 7** | **RN 8** | **RN 10** | **RN 11** | **RN 15** |
| **ED** | 0.513 | 0.248 | 0.183 | 0.184 | 0.067 | 0.072 | 0.059 | 0.054 | 0.046 | 0.043 | 0.044 |
| **TE** | 0.247 | 0.214 | 0.238 | 0.154 | 0.074 | 0.082 | 0.053 | 0.051 | 0.045 | 0.046 | 0.042 |
| **RS** | 0.118 | 0.168 | 0.167 | 0.196 | 0.097 | 0.084 | 0.078 | 0.058 | 0.055 | 0.050 | 0.048 |
| **EP** | 0.123 | 0.214 | 0.204 | 0.162 | 0.082 | 0.086 | 0.060 | 0.061 | 0.051 | 0.043 | 0.038 |
| **Scores** | | 0.226 | 0.197 | 0.176 | 0.074 | 0.078 | 0.060 | 0.054 | 0.048 | 0.044 | 0.043 |
| **Ranking** | | **1** | **2** | **3** | **5** | **4** | **6** | **7** | **8** | **9** | **10** |
| **Initial Ranking** | | **1** | **2** | **3** | **5** | **4** | **6** | **7** | **8** | **9** | **10** |

When we increase the environmental protection criterion by 5% and the ranking of alternatives do not change. From the table 42 above, above we can say that the environmental protection criterion is not the critical criterion.

Overall, from the sensitivity testing on our 10 alternatives projects, we can confirm that our results and ranking is quite robust to reasonably minor deviations from the initial results and ranking appear when economic development and road safety criterion weight is increased by 5 %.

### 5.4.2. Fuzzy Sensitivity analysis

The tables 43 below show the change in ranking when we increase by 5 % the economic development criterion and reduce by 5 % the transportation efficiency criterion:

| **Criteria** | | **Alternatives** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **weights** | **RN 1** | **RN 3** | **RN 4** | **RN 5** | **RN 6** | **RN 7** | **RN 8** | **RN 10** | **RN 11** | **RN 15** |
| **ED** | 0.536 | 0.1053 | 0.1086 | 0.1062 | 0.1004 | 0.1002 | 0.0985 | 0.0989 | 0.0967 | 0.0943 | 0.0909 |
| **TE** | 0.183 | 0.1111 | 0.1088 | 0.1091 | 0.1009 | 0.1010 | 0.0978 | 0.0977 | 0.0926 | 0.0910 | 0.0901 |
| **RS** | 0.192 | 0.1102 | 0.1113 | 0.1078 | 0.0983 | 0.1008 | 0.0961 | 0.0965 | 0.0936 | 0.0927 | 0.0926 |
| **EP** | 0.088 | 0.1042 | 0.1052 | 0.1083 | 0.1003 | 0.1006 | 0.1000 | 0.0971 | 0.0953 | 0.0941 | 0.0931 |
| Score | | 10.719% | 10.887% | 10.723% | 10.002% | 10.049% | 9.800% | 9.803% | 9.520% | 9.334% | 9.126% |
| Ranking | | **3** | **1** | **2** | **5** | **4** | **7** | **6** | **8** | **9** | **10** |
| Initial R | | **2** | **1** | **3** | **5** | **4** | **7** | **6** | **8** | **9** | **10** |

When we increase the economic development criterion by 5 %, the ranking of alternatives changes. From the table 43 above, we can observe that the second choice in the initial ranking become the third choice and the third choice in the initial ranking become the second choice. For this table we can say that the economic development criterion is not only the important criterion but also the critical criterion.

The tables 44 below show the change in ranking when we increase by 5 % the economic development criterion and reduce by 5 % the transportation efficiency criterion:

| Criteria | | Alternatives | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | weights | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
| **ED** | 0.436 | 0.1053 | 0.1086 | 0.1062 | 0.1004 | 0.1002 | 0.0985 | 0.0989 | 0.0967 | 0.0943 | 0.0909 |
| **TE** | 0.283 | 0.1111 | 0.1088 | 0.1091 | 0.1009 | 0.1010 | 0.0978 | 0.0977 | 0.0926 | 0.0910 | 0.0901 |
| **RS** | 0.192 | 0.1102 | 0.1113 | 0.1078 | 0.0983 | 0.1008 | 0.0961 | 0.0965 | 0.0936 | 0.0927 | 0.0926 |
| **EP** | 0.088 | 0.1042 | 0.1052 | 0.1083 | 0.1003 | 0.1006 | 0.1000 | 0.0971 | 0.0953 | 0.0941 | 0.0931 |
| Score | | 10.78 % | 10.89 % | 10.75 % | 10.01 % | 10.06 % | 9.793 % | 9.791 % | 9.48 % | 9.30 % | 9.12 % |
| Ranking | | **2** | **1** | **3** | **5** | **4** | **6** | **7** | **8** | **9** | **10** |
| Initial R. | | **2** | **1** | **3** | **5** | **4** | **7** | **6** | **8** | **9** | **10** |

When we increase the transportation efficiency by 5%, the ranking of alternatives do not change. From the table 44 above, we can observe that the sixth choice in the initial ranking become the seventh choice and the seventh choice in the initial ranking become the sixth choice. From the table we can say that the transportation efficiency criterion is also a critical criterion.

The tables 45 below show the change in ranking when we increase by 5 % the road safety criterion and reduce by 5 % the environmental protection criterion:

| **Criteria** | | **Alternatives** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **weights** | **RN 1** | **RN 3** | **RN 4** | **RN 5** | **RN 6** | **RN 7** | **RN 8** | **RN 10** | **RN 11** | **RN 15** |
| **ED** | 0.486 | 0.1053 | 0.1086 | 0.1062 | 0.1004 | 0.1002 | 0.0985 | 0.0989 | 0.0967 | 0.0943 | 0.0909 |
| **TE** | 0.233 | 0.1111 | 0.1088 | 0.1091 | 0.1009 | 0.1010 | 0.0978 | 0.0977 | 0.0926 | 0.0910 | 0.0901 |
| **RS** | 0.242 | 0.1102 | 0.1113 | 0.1078 | 0.0983 | 0.1008 | 0.0961 | 0.0965 | 0.0936 | 0.0927 | 0.0926 |
| **EP** | 0.038 | 0.1042 | 0.1052 | 0.1083 | 0.1003 | 0.1006 | 0.1000 | 0.0971 | 0.0953 | 0.0941 | 0.0931 |
| Score | | 10.78% | 10.92% | 10.74% | 9.99% | 10.05% | 9.78% | 9.79% | 9.49% | 9.31% | 9.12% |
| Ranking | | **2** | **1** | **3** | **5** | **4** | **7** | **6** | **8** | **9** | **10** |
| Initial R. | | **2** | **1** | **3** | **5** | **4** | **7** | **6** | **8** | **9** | **10** |

When we increase the road safety criterion by 5 % the ranking of alternatives does not change From the table 45 we can say that the environmental protection criterion is not the critical criterion.

The tables 46 below show the change in ranking when we increase by 5 % the environmental protection criterion and reduce by 5 % the road safety criterion:

| **Criteria** | | **Alternatives** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | **weights** | **RN 1** | **RN 3** | **RN 4** | **RN 5** | **RN 6** | **RN 7** | **RN 8** | **RN 10** | **RN 11** | **RN 15** |
| **ED** | 0.536 | 0.1053 | 0.1086 | 0.1062 | 0.1004 | 0.1002 | 0.0985 | 0.0989 | 0.0967 | 0.0943 | 0.0909 |
| **TE** | 0.183 | 0.1111 | 0.1088 | 0.1091 | 0.1009 | 0.1010 | 0.0978 | 0.0977 | 0.0926 | 0.0910 | 0.0901 |
| **RS** | 0.142 | 0.1102 | 0.1113 | 0.1078 | 0.0983 | 0.1008 | 0.0961 | 0.0965 | 0.0936 | 0.0927 | 0.0926 |
| **EP** | 0.138 | 0.1042 | 0.1052 | 0.1083 | 0.1003 | 0.1006 | 0.1000 | 0.0971 | 0.0953 | 0.0941 | 0.0931 |
| Score | | 10.69% | 10.86% | 10.72% | 10.01% | 10.05% | 9.82% | 9.81% | 9.53% | 9.34% | 9.13% |
| Ranking | | **3** | **1** | **2** | **5** | **4** | **6** | **7** | **8** | **9** | **10** |
| Initial R. | | **2** | **1** | **3** | **5** | **4** | **7** | **6** | **8** | **9** | **10** |

When we increase the environmental protection by 5%, the ranking of alternatives changes. From the table 46 above, we can observe that the second choice in the initial ranking become the third choice and the third choice in the initial ranking become the second choice From the table above, above we can say that the environmental protection criterion is also a critical criterion.

Overall, from the sensitivity testing on our 10 alternatives projects, we can confirm that our results and ranking is quite robust to reasonably minor deviations from the initial results and ranking appear when economic development and road safety criterion weight is increased by 5 %.

## 5.5.Cost estimates

The cost estimates is necessary for it will leads us to prepare the 3 years maintenance road works program. As said above in the methodology, the annually budget for paved road since 2008 given by Road Maintenance Fund (RMF) is estimated to 6, 5 billions of Rwandan francs. The table 47 below shows the unit price for different maintenance works in Rwandan Francs and in US dollar:

| | Routine Maintenance | Recurrent Maintenance | Periodic Maintenance |
|---|---|---|---|
| Unit Cost in RwF | **405,000** | **11,475,662.90** | **37,250,000** |
| Unit Cost in US | **591.24** | **16,752.79** | **54,379.56** |

Now the 3 years maintenance road works program done using AHP method in shown in the table 48 below:

| **Road name** | **Road ID** | **Rank** | **Lgth** | **ADT** | **Iri** | **Wrk** | **Budget** | **Fiscal Year** |
|---|---|---|---|---|---|---|---|---|
| Kigali-Huye-Akanyaru | RN 1 | 1 | 151.973 | 1,595 | 1.27 | ReM | 1,743,990,918 | ***First Year*** |
| Kigali-Kayonza-Rusumo | RN 3 | 2 | 165.699 | 1,471 | 2.17 | ReM | 1,901,505,867 | |
| Musanze-Rubavu | RN 4 | 3 | 56.719 | 1,504 | 1.49 | ReM | 650,888,124 | |
| Huye-Rusizi I | RN 6 | 4 | 52.729 | 478 | 3.53 | PeM | 1,964,155,250 | |
| **Total** | | | | | | | **6,260,540,159** | |
| Kayonza-Kagitumba | RN 5 | 5 | 116.318 | 653 | 3.61 | PeM | 4,332,845,500 | ***Second Year*** |
| Muhanga-Karongi | RN 7 | 6 | 77.837 | 366 | 2.24 | ReM | 893,231,173 | |
| Nyakinama-Musanze-Cyanika | RN 8 | 7 | 34 | 718 | 3.13 | PeM | 1,266,500,000 | |
| **Total** | | | | | | | **6,492,576,673** | |
| Bugarama-Ruhwa | RN 10 | 8 | 7.275 | 87 | 2.17 | RoM | 2,964,375 | ***Third Year*** |
| Muhanga-Ngororero-Muhanga | RN 11 | 9 | 98.69 | 260 | 2.21 | ReM | 1,132,533,172 | |
| Kicukiro-Nemba | RN 15 | 10 | | 832 | 1.36 | ReM | 690,582,442 | |
| **Total** | | | | | | | **1,826,061,989** | |

Now the 3 years maintenance road works program done using Fuzzy AHP method in shown in the table 49 below:

| **Road name** | **Road ID** | **Rank** | **Lgth** | **ADT** | **IRI** | **Wrk** | **Budget** | **Fiscal Year** |
|---|---|---|---|---|---|---|---|---|
| Kigali-Kayonza-Rusumo | RN 3 | 1 | 165.699 | 1,471 | 2.17 | ReM | 1,901,505,867 | ***First Year*** |
| Kigali-Huye-Akanyaru | RN 1 | 2 | 151.973 | 1,595 | 1.27 | ReM | 1,743,990,918 | |
| Musanze-Rubavu | RN 4 | 3 | 56.719 | 1,504 | 1.49 | ReM | 650,888,124 | |
| Huye-Rusizi I | RN 6 | 4 | 52.729 | 478 | 3.53 | PeM | 1,964,155,250 | |
| **Total** | | | | | | | **6,260,540,159** | |
| Kayonza-Kagitumba | RN 5 | 5 | 116.318 | 653 | 3.61 | PeM | 4,332,845,500 | ***Second Year*** |
| Nyakinama-Musanze-Cyanika | RN 8 | 6 | 34 | 718 | 3.13 | PeM | 1,266,500,000 | |
| Muhanga-Karongi | RN 7 | 7 | 77.837 | 366 | 2.24 | ReM | 893,231,173 | |
| **Total** | | | | | | | **6,492,576,673** | |
| Bugarama-Ruhwa | RN 10 | 8 | 7.275 | 87 | 2.17 | RoM | 2,964,375 | ***Third Year*** |
| Muhanga-Ngororero-Muhanga | RN 11 | 9 | 98.69 | 260 | 2.21 | ReM | 1,132,533,172 | |
| Kicukiro-Nemba | RN 15 | 10 | | 832 | 1.36 | ReM | 690,582,442 | |
| **Total** | | | | | | | **1,826,061,989** | |

## 5.6. Comparison of AHP and Fuzzy AHP ranking result

In this research, as comparative analysis of Analytic Hierarchy Process (AHP) and Fuzzy Analytic Hierarchy Process (Fuzzy AHP) for prioritization of alternatives paved road to be included in the 3 years maintenance road works program, we found that the final weight for scores for both method was quite similar as the criteria weight for AHP was N (0.513, 0.247, 0.168, 0.073) and for Fuzzy AHP was N' (0.486, 0.233, 0.192, 0.088).

From the table 50 below, we see that the ranking of the alternatives is quite the same for AHP and Fuzzy AHP:

| **Alternatives** | **AHP ranking** | **Fuzzy AHP ranking** |
|---|---|---|
| RN 1 | 1 | 2 |
| RN 3 | 2 | 1 |
| RN 4 | 3 | 3 |
| RN 5 | 5 | 5 |
| RN 6 | 4 | 4 |
| RN 7 | 6 | 7 |
| RN 8 | 7 | 6 |
| RN 10 | 8 | 8 |
| RN 11 | 9 | 9 |
| RN 15 | 10 | 10 |

As we said in the literature review Fuzzy AHP has been proved to be better to use when there is human vagueness and will help to solve the problem through a structured manner and in a simple process. AHP will help to make a best selection decision by using a weighting process within the current alternatives via pair wise comparisons.

It can be noted that using the criteria weight, the final ranking of AHP and of Fuzzy AHP are not competitors because they both give the same ranking of the alternatives. . The important point is that if the information/evaluations are certain, classical AHP method should be preferred but if the information/evaluations are not certain, fuzzy method should be preferred.

# VI. CONCLUSION AND RECOMMENDATION

## 6.1. Conclusion

As a decision support tool, Multi-criteria analysis (MCA) has been used in different sectors. In this researches it was applied in the appraisal of investment in transport policy and project planning. It is preferable over cost-benefit analysis (CBA) when intangible or non-monetized impacts are involved in the assessment.

MCA was advocated as the appraisal tool for the future [50], because of its ability to deal with complex, conflicting and incommensurable problems likely to characterize decisions when sustainability is taken into account [17]. However several issues need to be resolved to increase MCA's clientele at least on the CBA level in transport sector.

Some of these issues are: harmonization of principles and scales, elaboration of firm framework and less subjective scoring mechanism. The latter has been the focus of this study.

The aim of this research study was to prepare a protocol of prioritization for road maintenance works using AHP and Fuzzy AHP MCA model method in order to prepare a 3 years works program. The case study was the paved road network in Rwanda.

In this research, a review of multi-criteria analysis application in other sectors other than transport was done; and two novel scoring methods was identified and used in this work, AHP and Fuzzy AHP.

The study used 9-point scales for AHP method to evaluate and rating the impacts and the linguistic variable which was then converted into fuzzy numbers was used for the fuzzy AHP method. For both methods the aggregation method used was the arithmetic mean.

As said above, the data were drawn from the Rwanda National Paved Road with the objective to make a protocol of prioritization of the paved road section for maintenance road works for 3 successive years given the limited resource.

The criteria and sub-criteria used were found in the policy used in Rwanda such as Vision 2020, EDPRS 2, Public Transport Policy and Strategy for Rwanda, and Rwanda Strategic Transport Master Plan.

AHP as one of the most commonly used techniques when decision problem contain social, economic, technical and politic factors that need to be evaluated helps to select decision by comparing 10 different paved roads with respect four selected criteria: economic development, transportation efficiency, road safety and environmental protection. The result of the final ranking was tested the sensitivity and we found that, even if there were some minor changes in ranking, the ranking was robust.

Fuzzy AHP method also was applied to make a ranking among the 10 alternatives projects with respect to the same selected criteria: economic development, transportation efficiency, road safety and environmental protection; and the final ranking were tested the sensitivity and found that it was robust.

The study found that AHP as a MCA decision making techniques which is based on the linguistic evaluations has helped us to make a best selection decision by using a weighting process within the current alternatives via pair wise comparisons. And where there is uncertainty or in fuzzy environment, fuzzy numbers have to use for the evaluation due to the deviations of decision makers. The FAHP approach proved to be a convenient method in tackling practical multi-criteria decision making problems. Fuzzy AHP technique was used to synthesize the opinions of the decision makers to identify the weight of each criterion. It demonstrated the advantage of being able to capture the vagueness of human thinking and to aid in solving the research problem through a structured manner and a simple process.

## 6.2. **Recommendations for further researches**

Following the results we had with the available data, we advocate the following recommendation:

1. As we have annually a budget estimated around 17-18 billion Rwandan Francs allocated to unpaved road; we recommend to make the preparation of maintenance road works for unpaved road networks as well using the same criteria as it was found that their weight was quite robust and stable.
2. As the research study was focused on the practice of how the paved maintenance road works was prioritize in Rwanda. In the current practice, it was found that the road sections funded for maintenance works were not homogenous section. In order to improve the allocation of those funds, we will recommend the change in this practice and start to make priority according to the homogenous road section, by homogenous means the road sections having approximated the same annually average daily traffic.

3. Due to the time constraint imposed on this research, we have not applied the other MCA methods to analysis our data so that we can come out with a complete set of results and find how we can improve the scoring techniques of quantitative and qualitative criteria. We recommend to try other MCA method such fuzzy- TOPSIS or fuzzy PROMETHEE.

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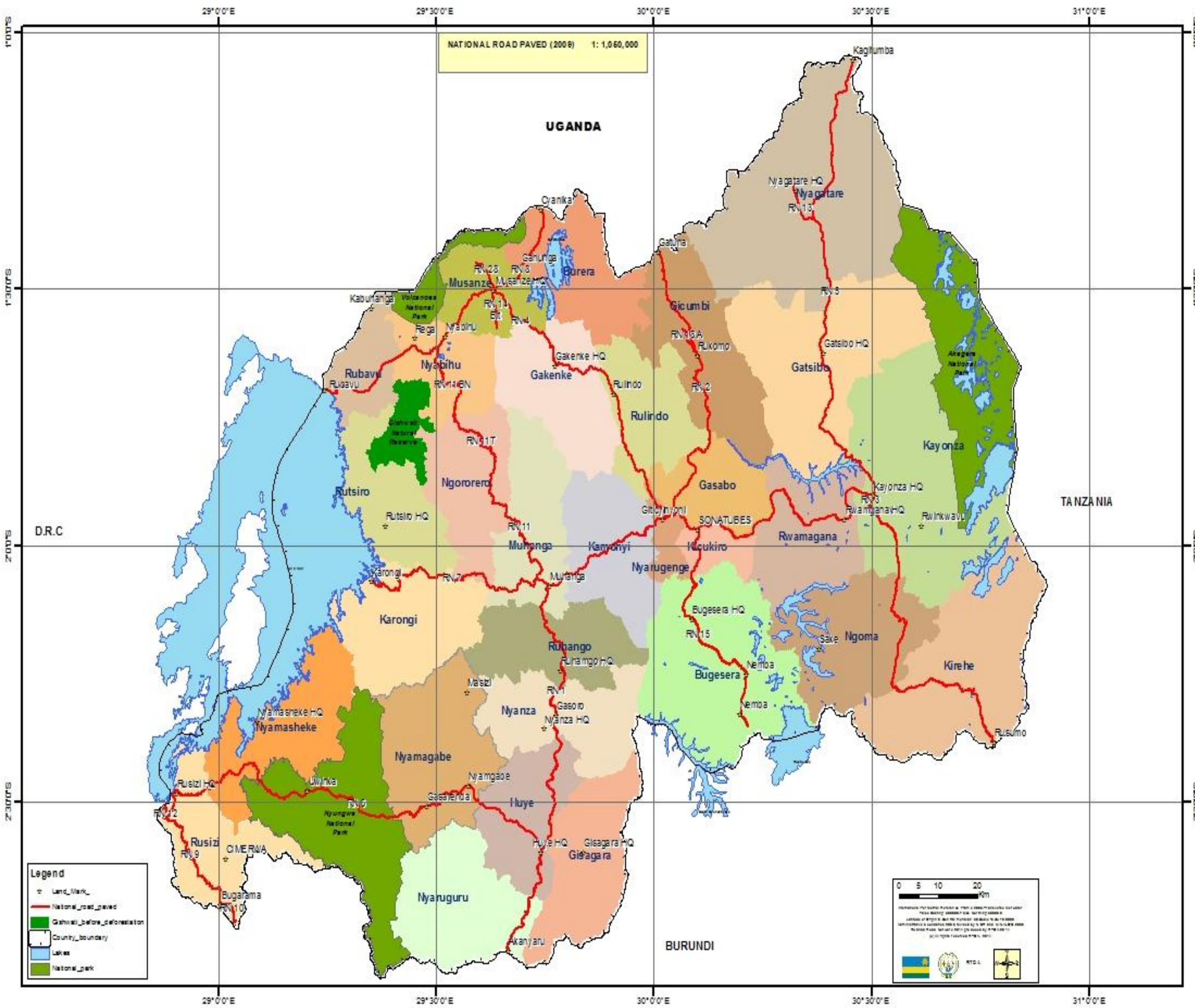
# VIII. APPENDIX

## Appendix 1: Rwanda National Paved Road Network



## Appendix 2: QUESTIONNAIRE AHP

### INTRODUCTION

This questionnaire is for the requirement of the Master in Transportation Engineering and Economics in the former Kigali Institute of Science and Technology (KIST). It serves for the ranking of the criteria and their sub-criteria for the final year dissertation entitle "Preparation of the Multi-Year Road Works Program using Multi-Criteria Analysis" using AHP (Analytical Hierarchical Process) and Fussy TOPSIS (Technique for Order Preference by Similarity to Ideal Solution).

The designed criteria and Sub-Criteria (between bracket)are **ECONOMIC DEVELOPMENT** (job creation, increase productivity and facilitate exports with neighbouring country), **TRANSPORTATION EFFICIENCY** (ADT and Road Condition), **ENVIRONMENTAL PROTECTION** (reduction of negative environmental impact) and **ROAD SAFETY** (reduce of annual accident number); Economic Development, Environmental protection are qualitative while Transport Efficiency and Road Safety are quantitative.

This questionnaire consists of two parts, the first one is for respondent information, and the second part is for the weight of the criteria to take into consideration for the preparation of road work program. Those criteria and their respective sub-criteria were identified through the objectives of Rwanda policies, such as Vision 2020, EDPRS 2, Public Transport Policy and Strategy for Rwanda, and Rwanda Strategic Transport Master Plan, and through the experience of other countries I have read in the internet, especially in the practices used in United State of America.

Here is the definition of three primary criteria:

4. Wikipedia defines Economic Development (**ED**) as the continuous and determined effort of policy makers and communities that promotes the quantitative and qualitative changes in the economy of a region through development of human capital
5. According the Organization for Economic Co-operation and Development (OECD), Environmental protection refers to any activity to protect, maintain or restore the quality of environmental media through preventing the emission of pollutants or reducing the presence of polluting substances in environmental media, whether on individual, organizational or global (international) level. It may consist of: changes in characteristics

of goods and services, changes in consumption patterns, changes in production techniques, treatment or disposal of residuals in separate environmental protection facilities, recycling, and prevention of degradation of the landscape and ecosystems

6. According to Wikipedia, **Road traffic safety** refers to methods and measures for reducing the risk of a person using the road network being killed or seriously injured. The users of a road include pedestrians, cyclists, motorists, their passengers, and passengers of on-road public transport, mainly buses and trams. Best-practice road safety strategies focus upon the prevention of serious injury and death crashes in spite of human fallibility (which is contrasted with the old road safety paradigm of simply reducing crashes assuming road user compliance with traffic regulations).

*N.B: This research Study is for academic purpose*

**INSTRUCTIONS**

- Ticking in more than one box on the same low of variable is not allowed.
- You can use any symbol you want for ticking (i.e: X,…..).
- For any clarification do not hesitate to contact us through e-mail address: munyamena07@gmail.com or on the phone number: (+250)788519022.

**PART ONE**

| **PARICIPANTS DETAIL** | | **Frequency** |
|---|---|---|
| Age | <25 | |
| | 25-29 | |
| | 30-34 | |
| | 35-39 | |
| | 40-44 | |
| | 45-49 | |
| | ≥50 | |
| Sex | Male | |
| | Female | |
| Education | Secondary | |
| | Pre-University | |
| | University/Bsc Degree | |
| | Post Graduate/Msc Degree | |
| Type of Organization working in | Public Institution | |
| | Academic Institution | |
| | Private (Consultant) | |
| Respondent working experience | < 4 years | |
| | 4-8 years | |
| | 8 -12 years | |
| | >12 years | |
| Occupational level | Executive | |
| | Managerial | |

**PART TWO:**

For multiple criteria inventory classification, four criteria were included. All the criteria are positively related to the importance level. The criteria are:

1. **Economic Development (ED)**
2. **Transportation Efficiency (TE)**

3. **Road Safety (RS)**
4. **Environmental Protection (EP)**

**Questionnaire 1: Prioritization of Criteria for Road works Program using AHP**

Table1: Triangular Fuzzy Scale for the importance Weight of Criteria and Sub-Criteria

| Importance/ weights | Definition |
|---|---|
| 1 | equal |
| 3 | Weakly important |
| 5 | Strongly more important |
| 7 | very strongly more important |
| 9 | absolutely more important |
| 2,4,6,8 | Intermediate values between the two adjacent judgments |

Table 2: Judgments matrix for Criteria using Fuzzy AHP

| Criteria | Economic Development | Transportation Efficiency | Road Safety | Environmental Protection |
|---|---|---|---|---|
| Economic Development | 1 | | | |
| Transportation Efficiency | | 1 | | |
| Road Safety | | | 1 | |
| Environmental Protection | | | | 1 |

Table 3: Judgments matrix for Sub-Criteria of Economic Development using Fuzzy AHP

| Sub-Criteria | Job Creation | Increase productivity | Facilitate Exports |
|---|---|---|---|
| Job Creation | 1 | | |

| | | | |
|---|---|---|---|
| Increase productivity | | 1 | |
| Facilitate Exports | | | 1 |

Table 4: Judgments matrix for Sub-Criteria of Transportation Efficiency using Fuzzy AHP

| Sub-Criteria | Traffic (ADT) | Road Condition (IRI) |
|---|---|---|
| Traffic (ADT) | 1 | |
| Road Condition (IRI) | | 1 |

Table 5: Judgments matrix for Alternatives compare to Economic Development Criterion

| Alternatives | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 1 | 1 | | | | | | | | | |
| RN 3 | | 1 | | | | | | | | |
| RN 4 | | | 1 | | | | | | | |
| RN 5 | | | | 1 | | | | | | |
| RN 6 | | | | | 1 | | | | | |
| RN 7 | | | | | | 1 | | | | |
| RN 8 | | | | | | | 1 | | | |
| RN 10 | | | | | | | | 1 | | |
| RN 11 | | | | | | | | | 1 | |
| RN 15 | | | | | | | | | | 1 |

Table 6: Judgments matrix for Alternatives compare to Transportation Efficiency Criterion

| Alternatives | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 1 | 1 | | | | | | | | | |
| RN 3 | | 1 | | | | | | | | |
| RN 4 | | | 1 | | | | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 5 | | | | 1 | | | | | | |
| RN 6 | | | | | 1 | | | | | |
| RN 7 | | | | | | 1 | | | | |
| RN 8 | | | | | | | 1 | | | |
| RN 10 | | | | | | | | 1 | | |
| RN 11 | | | | | | | | | 1 | |
| RN 15 | | | | | | | | | | 1 |

Table 7: Judgments matrix for Alternatives compare to Road Safety Criterion

| Alternatives | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 1 | 1 | | | | | | | | | |
| RN 3 | | 1 | | | | | | | | |
| RN 4 | | | 1 | | | | | | | |
| RN 5 | | | | 1 | | | | | | |
| RN 6 | | | | | 1 | | | | | |
| RN 7 | | | | | | 1 | | | | |
| RN 8 | | | | | | | 1 | | | |
| RN 10 | | | | | | | | 1 | | |
| RN 11 | | | | | | | | | 1 | |
| RN 15 | | | | | | | | | | 1 |

Table 8: Judgments matrix for Alternatives compare to Environmental Protection Criterion

| Alternatives | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 1 | 1 | | | | | | | | | |
| RN 3 | | 1 | | | | | | | | |
| RN 4 | | | 1 | | | | | | | |
| RN 5 | | | | 1 | | | | | | |

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 6 | | | | | 1 | | | | | |
| RN 7 | | | | | | 1 | | | | |
| RN 8 | | | | | | | 1 | | | |
| RN 10 | | | | | | | | 1 | | |
| RN 11 | | | | | | | | | 1 | |
| RN 15 | | | | | | | | | | 1 |

## Appendix 3: QUESTIONNAIRE Fuzzy AHP

### INTRODUCTION

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Here is the definition of three primary criteria:

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techniques, treatment or disposal of residuals in separate environmental protection facilities, recycling, and prevention of degradation of the landscape and ecosystems

9. According to Wikipedia, **Road traffic safety** refers to methods and measures for reducing the risk of a person using the road network being killed or seriously injured. The users of a road include pedestrians, cyclists, motorists, their passengers, and passengers of on-road public transport, mainly buses and trams. Best-practice road safety strategies focus upon the prevention of serious injury and death crashes in spite of human fallibility (which is contrasted with the old road safety paradigm of simply reducing crashes assuming road user compliance with traffic regulations).

*N.B: This research Study is for academic purpose*

**INSTRUCTIONS**

- Ticking in more than one box on the same low of variable is not allowed.
- You can use any symbol you want for ticking (i.e: X,…..).
- For any clarification do not hesitate to contact us through e-mail address: munyamena07@gmail.com or on the phone number: (+250)788519022.

**PART ONE**

| PARICIPANTS DETAIL | | Frequency |
|---|---|---|
| Age | <25 | |
| | 25-29 | |
| | 30-34 | |
| | 35-39 | |
| | 40-44 | |
| | 45-49 | |
| | ≥50 | |
| Sex | Male | |
| | Female | |
| Education | Secondary | |
| | Pre-University | |
| | University/Bsc Degree | |
| | Post Graduate/Msc Degree | |
| Type of Organization working in | Public Institution | |
| | Academic Institution | |
| | Private (Consultant) | |
| Respondent working experience | < 4 years | |
| | 4-8 years | |
| | 8 -12 years | |
| | >12 years | |
| Occupational level | Executive | |
| | Managerial | |

**PART TWO:**

For multiple criteria inventory classification, four criteria were included. All the criteria are positively related to the importance level. The criteria are:

1. **Economic Development (ED)**
2. **Transportation Efficiency (TE)**
3. **Road Safety (RS)**
4. **Environmental Protection (EP)**

**Questionnaire 1: Prioritization of Criteria for Road works Program using AHP and Fuzzy AHP**

Table1: Triangular Fuzzy Scale for the importance Weight of Criteria and Sub-Criteria

| Linguistic scale | Triangular fuzzy scale | Fuzzy Number |
|---|---|---|
| equal | (1,1,1) | $1^-$ |
| Weakly important | (1,2,3) | $3^-$ |
| Strongly more important | (3,4, 5) | $5^-$ |
| very strongly more important | (5,6,7) | $7^-$ |
| absolutely more important | (7,8,9) | $9^-$ |

Table 3: Judgments matrix for Criteria using Fuzzy AHP

| Criteria | Economic Development | Transportation Efficiency | Road Safety | Environmental Protection |
|---|---|---|---|---|
| Economic Development | $1^-$ | | | |
| Transportation Efficiency | | $1^-$ | | |
| Road Safety | | | $1^-$ | |
| Environmental Protection | | | | $1^-$ |

Table 4: Judgments matrix for Sub-Criteria of Economic Development using Fuzzy AHP

| Sub-Criteria | Job Creation | Increase productivity | Facilitate Exports |
|---|---|---|---|
| Job Creation | 1- | | |
| Increase productivity | | 1- | |
| Facilitate Exports | | | 1- |

Table 5: Judgments matrix for Sub-Criteria of Transportation Efficiency using Fuzzy AHP

| Sub-Criteria | Traffic (ADT) | Road Condition (IRI) |
|---|---|---|
| Traffic (ADT) | 1- | |
| Road Condition (IRI) | | 1- |

Table 6: Judgments matrix for Alternatives compare to Economic Development Criterion

| Alternatives | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 1 | 1- | | | | | | | | | |
| RN 3 | | 1- | | | | | | | | |
| RN 4 | | | 1- | | | | | | | |
| RN 5 | | | | 1- | | | | | | |
| RN 6 | | | | | 1- | | | | | |
| RN 7 | | | | | | 1- | | | | |
| RN 8 | | | | | | | 1- | | | |
| RN 10 | | | | | | | | 1- | | |
| RN 11 | | | | | | | | | 1- | |
| RN 15 | | | | | | | | | | 1- |

Table 7: Judgments matrix for Alternatives compare to Transportation Efficiency Criterion

| Alternatives | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 1 | 1- | | | | | | | | | |
| RN 3 | | 1- | | | | | | | | |
| RN 4 | | | 1- | | | | | | | |
| RN 5 | | | | 1- | | | | | | |
| RN 6 | | | | | 1- | | | | | |
| RN 7 | | | | | | 1- | | | | |
| RN 8 | | | | | | | 1- | | | |
| RN 10 | | | | | | | | 1- | | |
| RN 11 | | | | | | | | | 1- | |
| RN 15 | | | | | | | | | | 1- |

Table 8: Judgments matrix for Alternatives compare to Road Safety Criterion

| Alternatives | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 1 | 1- | | | | | | | | | |
| RN 3 | | 1- | | | | | | | | |
| RN 4 | | | 1- | | | | | | | |
| RN 5 | | | | 1- | | | | | | |
| RN 6 | | | | | 1- | | | | | |
| RN 7 | | | | | | 1- | | | | |
| RN 8 | | | | | | | 1- | | | |
| RN 10 | | | | | | | | 1- | | |
| RN 11 | | | | | | | | | 1- | |
| RN 15 | | | | | | | | | | 1- |

Table 9: Judgments matrix for Alternatives compare to Environmental Protection Criterion

| Alternatives | RN 1 | RN 3 | RN 4 | RN 5 | RN 6 | RN 7 | RN 8 | RN 10 | RN 11 | RN 15 |
|---|---|---|---|---|---|---|---|---|---|---|
| RN 1 | 1- | | | | | | | | | |
| RN 3 | | 1- | | | | | | | | |
| RN 4 | | | 1- | | | | | | | |
| RN 5 | | | | 1- | | | | | | |
| RN 6 | | | | | 1- | | | | | |
| RN 7 | | | | | | 1- | | | | |
| RN 8 | | | | | | | 1- | | | |
| RN 10 | | | | | | | | 1- | | |
| RN 11 | | | | | | | | | 1- | |
| RN 15 | | | | | | | | | | 1- |