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**The American University in Cairo
School of Science and Engineering**

**INTEGRATED ASSET MANAGEMENT SYSTEM FOR
PERFORMANCE-BASED ROAD MAINTENANCE CONTRACTS**

A Thesis Submitted to

Department of Construction and Architectural Engineering

In partial fulfillment of the requirements for the degree of

Master of Science

In

Construction Management

By

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MAY 2014

DEDICATION

“Success or Failure is an own decision”

I dedicate my thesis work to my grandparents, parents, and many close friends. A special feeling of appreciation to my loving parents, Amr and Ghada, whose inspiring and impulsive words gave me a high momentum to exert all my efforts towards success. My brother, Ehab has been always present beside me and is very special to my heart.

I dedicate this work and give special thanks to my closest friends Osama Maamoun and Nadine Essam for being there for me throughout the entire program. Both of you have been my best cheerleaders.

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The American University in Cairo

INTEGRATED ASSET MANAGEMENT SYSTEM FOR PERFORMANCE-BASED ROAD MAINTENANCE CONTRACTS

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ABSTRACT

Performance-based maintenance contracts (PBMC) for highways are increasingly becoming an attractive mechanism for transferring activities traditionally undertaken by the public sector to private entities. Increased financial pressures on governments, demands for improved service levels by highway users, and the operational efficiencies offered by the private sector, all create a strong business case for PBMC. In order to enable government road agencies and private sector investors to engage in the use of PBMC, there is a need for quantitative tools that allow both entities to 1) Properly structure the PBMC in terms of risk allocation, 2) Develop appropriate levels for service level penalties and incentives in the contract, 3) Determine appropriate targets for highway level of service, and 4) Determine the most cost-effective set of road maintenance and rehabilitation (M&R) activities to be undertaken throughout the duration of the contract.

This research developed a GIS-based Integrated Highway Asset Management System (IHAMS), which extends typical functionality of traditional pavement management systems to cover specific contractual requirements of PBMC. The system allows the analysis of both network-level and project-level asset management decisions. Defect-specific pavement deterioration models are developed using multivariate regression. Stochastic network-level deterioration models are developed using markov chains. Life cycle costing models are developed to cover specific financial obligations in

PBMC like penalties and incentives, in addition to traditional M&R expenditure. A GA-based optimization module is used to trade-off various decision scenarios that are beneficial to both road maintenance contracts and road agencies. A case study for the Cairo-Ismailiyah desert highway is used to demonstrate the capability of the system.

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LIST OF SYMBOLS

- $P(x)$ is the distribution of variants over all possible fraction variants
- $P(p)$ is the prior distribution
- $P(x|p)$ is the sampling distribution
- $P(p|x)$ is the posterior distribution
- N_s is the number of samples
- n is the total number of inspection samples
- S is the random start
- IRI_{in_i} is the annual initial IRI before applying any M&R strategy
- Rd_{in_i} is the annual initial rutting depth before applying any M&R strategy
- SR_{in_i} is the annual initial surface rating before applying any M&R strategy
- AG_{in_i} is the annual initial alligator cracking before applying any M&R strategy
- PCI_{in_i} is the annual initial PCI before applying any M&R strategy
- N is the number of years (age) of the highway
- T is the annual traffic growth rate (%)
- AADT is the annual average growth rate
- IRI_{cal_i} is the predicted IRI after M&R application
- Rd_{cal_i} is the predicted rutting depth after M&R application
- SR_{cal_i} is the predicted surface rating after M&R application

- AG_{cal_i} is the predicted alligator cracking after M&R application
- PCI_{cal_i} is the predicted PCI after M&R application
- HCI is the overall highway condition index
- j is the M&R strategies counter
- m is the total number of maintenance strategies
- i is the number of years (age) counter
- n is the total number of contractual years
- Ap_j is the applicability index (0 → Not Applicable (N/A) and 1 → Applicable)
- X_{ij} is the decision variable resulting from the optimization engine where; it is represented on a numerical integers ranging from (0 → Do Nothing to m → total number of maintenance strategies)
- PRM_{total} is the total preventative maintenance costs
- RB_{total} is the total rehabilitation costs
- PEN_{total} is the total penalties as per defined in the contract
- INC_{total} is the total incentives as per defined in the contract
- LCC_{total} is the total LCC spent for this highway
- L_r is the length of the road assigned for preventative maintenance
- PRM_u is the unit cost for the preventative maintenance
- i_n is the annual inflation rate (%)
- A_r is the area of the highway assigned for M&R

- Ap_i is the applicability index (0 → Not applicable (N/A), 1 → Applicable). It differs for each cost item based on the application criteria defined previously in the contract
- RB_{u_j} is the unit cost for each rehabilitation strategy
- d is the KPI calculator
- r is the total number of KPIs' contractually defined under the PBRMC
- P_{u_d} is the penalty unit cost for each KPI solely
- Inc_{u_d} is the incentive unit cost for each KPI solely
- PCI_{LT} is the PCI hard constraint in which the annual PCI and the overall HCI resulting from the M&R action plan couldn't exceed
- SR_{LT} is the surface rating hard constraint in which the surface rating resulting from the M&R action plan couldn't exceed
- IRI_{LT} is the IRI hard constraint in which the IRI resulting from the M&R action plan couldn't exceed
- AG_{LT} is the alligator cracking hard constraint in which the alligator cracking resulting from the M&R action plan couldn't exceed
- $P_{max,d}$ is the maximum penalty limit for each KPI chosen by the user
- $P_{min,d}$ is the minimum penalty limit for each KPI chosen by the user
- $Inc_{max,d}$ is the maximum incentive limit for each KPI chosen by the user
- $Inc_{min,d}$ is the minimum incentive limit for each KPI chosen by the user
- HBT_i is the annual highway budget constraint. The NPV equations are applicable where; $HBT_n = HBT_1 * (1 + in)^n$

- DEV_{total} is the total budget and condition deviation
- LCC_{limit} is the total budget required for the highway under study
- HCI_{limit} is the minimum allowable highway condition index that could be reached even after applying the P/I system
- NTB is the network budget
- k is the number of highways counter
- h is the total number of highways
- NLCC is the network life cycle costs
- z is the number of highways in the network
- q is the total number of the highways in the network
- w is the weight of each highway in the network
- NCI_{LT} is the NCI hard constraint in which the annual and/or the overall NCI resulting from the M&R action plan couldn't exceed
- NBT_i is the annual network budget constraint. The NPV equations are applicable where; $NBT_n = NBT_1 * (1 + in)^n$
- $NDEV_{total}$ is the total network budget and condition deviation
- $NLCC_{limit}$ is the total budget required for the network under study
- NCI_{limit} is the minimum allowable network condition index that could be reached even after applying the P/I system
- AHCI is the Highway Condition Index
- SCI is the Segment Condition Index
- OTM is the original transition probability matrix

- CCM is the current condition matrix
- NTM is the new transition matrix
- P_i is the annual probability that the highway will be in this condition state
- c is the condition state counter (Excellent, Good, Fair, Poor, Failing)
- X_c is the M&R percentage chosen by the optimization engine to meet the KPIS' and meet the objective
- C_c is the current percentage of the highway length for each condition state
- PM_i is the annual probability matrix
- CM_i is the annual condition matrix
- HL_{ic} is the annual highway length for each condition state (c)
- f is the total number of condition states

ACRONYMS

- **AADT:** Annual Average Daily Traffic
- **ACR:** Actual Condition Rating
- **ACRS:** Actual Condition Rating System
- **AI:** Artificial Intelligence
- **ANN:** Artificial Neural Networks
- **BCA:** Benefit-Cost Analysis
- **BCR:** Benefit-Costs Ratio
- **CAPMAS:** Central Agency for Public Mobilization and Statistics
- **CE:** Cost-Efficiency
- **CI:** Confidence Interval
- **DSS:** Decision-Support System
- **FHWA:** Federal Highway Administration
- **GARBLT:** General Authority for Roads, Bridges and Land Transport
- **GAs':** Genetic Algorithms
- **GIS:** Geographic Information System
- **HMA:** Hot mix Asphalt
- **IHAMS:** Integrated Highway Asset Management System
- **IRI:** International Roughness Index
- **KPIs':** Key Performance Indicators

- **LCC:** Life Cycle Costing
- **LOS:** Level of Service
- **LRSs:** location Referencing Systems
- **M&R:** Maintenance/Rehabilitation actions
- **MLP:** Multi-Layer Perceptron
- **NCI:** Network Condition Index
- **NHS:** National Highway System
- **NPV:** Net Present Value
- **OECD:** Organization for Economic Co-Operation and Development
- **P/I System:** Penalties and Incentives System
- **PBC:** Performance-Based Contracts
- **PBRMC:** Performance-Based Road Maintenance Contracts
- **PCGA:** Pre-Constrained GAs'
- **PCI:** Pavement Condition Index
- **PM:** Preventative Maintenance
- **PMS:** Pavement Management System
- **PPP:** Public-Private Partnership
- **QC:** Quality Control
- **QOS:** Quality of Service
- **SCI:** Segment Condition Index

- **SD or σ** : Standard Deviation
- **SGA**: Simple GAs'
- **SH**: State Highway
- **SMART**: Specific, Measurable, Achievable, Realistic and Timely to Schedule
- **SOM**: Self-Organizing Map
- **SP**: Safety Procedures
- **TOR**: Timeless of Response
- **V/C Ratio**: Volume/Capacity Ratio
- **VCI**: Visual Condition Index
- **WHO**: World Health Organization
- **USD**: US Dollar (\$)

1 CHAPTER 1 - INTRODUCTION

This chapter starts by discussing performance-based road maintenance contracts (PBMC) and how they are related to pavement management system (PMS). The chapter goes on to discuss the use of Geographic Information Systems (GIS) as a visualization tool for PMS. The chapter finally highlights the problem statement, need for the research, objectives and outcomes of the thesis.

1.1 Background

Public infrastructure services are a key enabler of social and economic development. Infrastructure services provide for shelter, mobility, energy, clean water, sanitation and communication services that are required for communities to thrive. Proper management of these vast systems is necessary to ensure that our communities continue to prosper. Infrastructure asset management is defined as “the systematic, coordinated planning and programming of investments or expenditures, design, construction, maintenance, operation, and in-service evaluation of physical facilities” (Haas et al., 1994). It covers all the activities that guarantees a minimal acceptable infrastructure level of service to be brought up to the public. These activities range from the initial information acquisition, required for calculating the public need for a specific type of infrastructure, to the maintenance and rehabilitation needed for meeting a proper level of service, from the infrastructure preliminary design and construction to the monitoring and evaluation process.

Infrastructure asset management is not just about managing an existing facility to deliver intended service, but it is more about critical decision for properly investing the limited governmental resources to both; meet the need for building new infrastructure, and keep the existing infrastructure within an acceptable level of service. Defferred investment in existing infrastructure systems in many developing countries has led to declines in level of service provided by the systems, the need for costly replacement, and in some cases sudden catastrophic failures.

Transportation infrastructure (roads, railways, airports and seaports) represents a key infrastructure to all the countries' economies. The length of roads in Canada is 521,952 miles where; 63% are earth and gravel and 37% are paved roads. The annual expenditures on pavements was more than \$4 billion (Madanat, 1997). Likewise, the National Highway System (NHS) reported that the annual cost to maintain the United States (U.S) system at existing level condition is nearly \$50 billion. In spite of this, the U.S only spends an annual amount of \$25 billion resulting in an average ranking of D (poor) for the roads as an example (ASCE, 2013). The estimated cost to bring up the entire system up from its current condition (poor) to a good condition is \$200 billion. From this point, it is visible that a vital need for re-structuring the pavement preservation strategies need to be considered (FHWA, 2002).

The World Bank (1988) has conducted a study on the roads of 85 developing countries. The study realized that 25% of the paved highways outside urban areas were in a failing condition attributable to the un-suitable applied maintenance strategies. Additionally, the loss could have been saved by the means of preventive maintenance totalling \$12 billion. In the bargain, 40% of the paved roads are in a serious need for routine maintenance in the next five-year plan totalling an amount of \$40 billion. Conversely, the amount will reach \$100 billion if no action was taken. The severity this catastrophe reached was due to the negligence of the slow and indiscernible deterioration rate for the newly paved road in the first service life-span, and as a consequence, the rapid and visible deterioration requires a four to five times higher maintenance costs compared to the timely preventive maintenance (The World Bank, 1988).

Nevertheless, The World Bank pinpointed that the routine and periodic maintenance needed just to safeguard the roads from further deterioration between 1986 – 1999 was guesstimated to play around \$4.6 billion/year totalling \$46 billion over the 13 years period between 1986 – 1999. However, \$3 billion would have been saved if the maintenance was applied on a timely basis. Besides, the rehabilitation costs were estimated to increase by an amount of \$20 billion at the time when the major rehabilitation is applied, if the maintenance needs for 20% of the roads in a fair condition weren't properly accomplished at the right time (The World Bank, 1988).

After decades of brainstorming and thinking, highways was chosen to be the area of study of this research. Highways is a crucial infrastructure component constituting more than 50% of the total transportation infrastructure expenditures. Inadequate pavement management was apparent, especially in the last thirty years (Mubaraki, 2010). As a result, a massive increase in the cost of restoring the deteriorated pavements was apparent where; the maintenance costs dramatically increased by three to five times compared to what have been for proper timely and effective maintenance. In addition, from the eighty five countries that received assistance, from the world bank, for road maintenance, a quarter of the already paved roads needed reconstruction as well as another third for the unpaved roads. This work will approximately range between \$40 to \$45 billion, which could have been saved in case of timely preventative maintenance reaching only \$12 billion and saving the rest \$30 billion. Moreover, another 40% of the paved roads in these countries require strengthening these days or maybe in the next few years. This work will cost another \$40 to \$45 billion over the next ten years. That brings a total of \$80 to \$90 billion for restoration and maintenance of the existing roads (The World Bank, 1988).

Occupying the northeast corner of the African continent, the Egyptian population has tripled in the last 50 years from 27.6 million in 1960 to 82.5 million in 2012 according to the last national statistics (CAPMAS, 2012). As a result of this extremely high population increase, newly build infrastructure should be built to shield the increased population by main services (potable and irrigation water treatment plants, pipelines, electricity, highways and public transportation, etc...). Adding to this extremely high population increase, the governmental limited resources limit the infrastructure development, to meet the population needs, which act as another aspect that should be taken into consideration in critical infrastructure decisions. Besides, the governmental failure for optimally allocating the expenditures, in order to maintain the minimal acceptable level of service, was obvious especially in the last ten years. As an example, the national budget for the roads maintenance suddenly jumped from EGP 280 million in 2006/2007 to EGP 4.1 billion in 2007/2008 due to the extremely poor condition the roads have reached (Al-Ahram, 2008).

This research is aiming to introduce an integrated “Highway Asset Management” approach with “Geographic Information System” through a very special type of contracts named as “Performance Based Contract”. The research will firstly illustrate the key aspects of performance-based contracts and how it is directly related to the highway asset management. Then, it will highlight on the “Pavement Management System” as a part of the highway asset management. After that, the benefits of creating an automated geographic information system will be explored for a better expenditures allocation and highway management as well. Finally, this research will develop an automated system, which can be used for the future application of performance-based contracts on the existing pavements, to improve the pavement performance and deliver a better level of service for the public.

1.2 Research Themes

As mentioned earlier on the previous section, this research focuses on the pavements, one of the main transportation infrastructure services, to be the intended study area. In this section, the author will provide a brief overview about the different research themes in addition to the relationship between them. This section will be divided into two parts:

1. Performance-Based Road Maintenance Contracts
2. Highway Asset Management “Pavement Management System”

1.2.1 Performance-Based Road Maintenance Contracts

Performance-based contract is a special type of contracts that was conceptually designed to increase both the efficiency and effectiveness of the pavement maintenance. Performance based contracts have been applied for the maintenance of the pavements in many developing and developed countries beginning with Canada (1988), Argentina (1990), and ending with Finland (1998), Zambia (1999), etc.... Martin defined the performance based contracting as “a type of contracts that focus on the outputs, quality, and outcome of the service provision and may tie at least a portion of a maintenance contractors’ payment as well as any contract extension or renewal to their achievement.” (Martin, 2003).

Performance-Based Road Maintenance Contracts (PBRMC) covers an array of activities needed to maintain a road service quality level for users. Figure 1-1 illustrates the main activities that should take place in order to maintain the desired road service quality level (The World Bank, 2002):

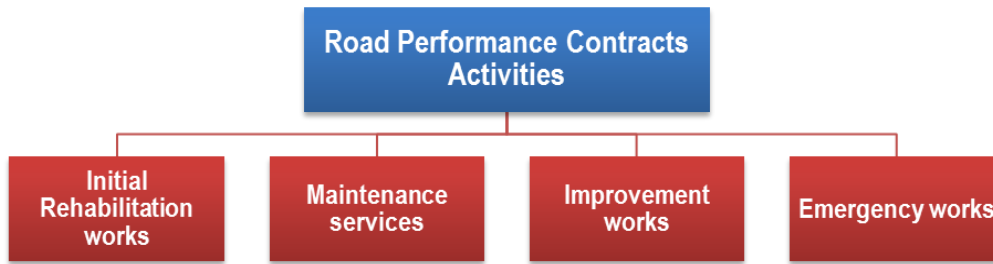


Figure 1-1: Performance based road maintenance contracts activities (The World Bank, 2002)

As shown in Figure 1-1, the PBRMC activities begins with carrying out the initial rehabilitation works at the initial stage of the contract to bring the road up to pre-defined standards. The second activity is the regular maintenance services, which are the physical works, applied on the roads to maintain the agreed service quality levels and it includes all the activities related to the management and evaluation of the road under the contract. The third activity is the improvement works, which are specified by the employer in order to add new characteristics to the roads related to new traffic, safety or any other considerations. Finally, the last activity is the emergency works, which include any activity needed to reinstate the roads after any damages resulting from unforeseen natural phenomena (such as strong storms, flooding and earthquakes) with imponderable consequences (The World Bank, 2002).

The maintenance contractors should present their financial offer in the form of four types of activities as follows:

1. Initial rehabilitation works: It is represented through a lump-sum amount. The maintenance contractor should indicate the quantities of measurable outputs that will be executed in order to achieve the performance standards pre-defined in the contract.
2. Maintenance services: It is represented through a form of monthly lump-sum payment in case of meeting the performance standards defined in the contract.

3. Improvement works: It is represented through a form of unit prices for outputs of each type of improvement works. The improvement works payment will be calculated based on these unit prices defined by the maintenance contractor in the signed contract documents.
4. Emergency works: It is represented through unit prices in a form of a traditional bill of quantities. The emergency works payment is made on a case-by-case basis, under the basis of the estimated quantities.
5. Price adjustment: It is a clause defined in the contract to compensate the maintenance contractors for any increase in the cost indexes. This clause is applicable to all prices and activities mentioned above.

For a successful PBRMC, two key issues have to be considered. The first one is a proper definition of “Key Performance Indicators” to be able to accurately evaluate and assess the service quality level performed by the maintenance contractor. The second one is introducing an adequate penalties and incentives (P/I) system that gives the maintenance contractor the opportunity to reach better quality levels in order to gain the pre-defined incentives and on the other hand, applies strict penalties on the maintenance contractor who does not meet the minimal acceptable service quality level represented by the key performance indicators (KPIs’). As for the KPIs’, they should be SMART indicators, which are Specific, Measurable, Achievable, Realistic, and Timely to schedule. In addition, they should also act as a direct indicator for the pavement physical condition to ensure adequate service quality for the pavement under the contract.

Moving to the P/I system, one of the main issues that were recognized after the application of PBRMC was the inadequate incentives and high penalties. It has been apparent that the inadequate incentives and extremely high penalties, proposed by the employer, tended to force the maintenance contractors to significantly increase their fixed monthly maintenance costs for the monthly services to cover any risks encountered throughout the contractual period.

The main benefits for applying PBRMC are as follows:

1. PBRMC partially transfers the risk of not complying with the service quality standards (KPIs') to the maintenance contractor. Figure 1-2 shows the road maintenance risk distribution beginning with the in-house maintenance and ending with the long-term road concessions.

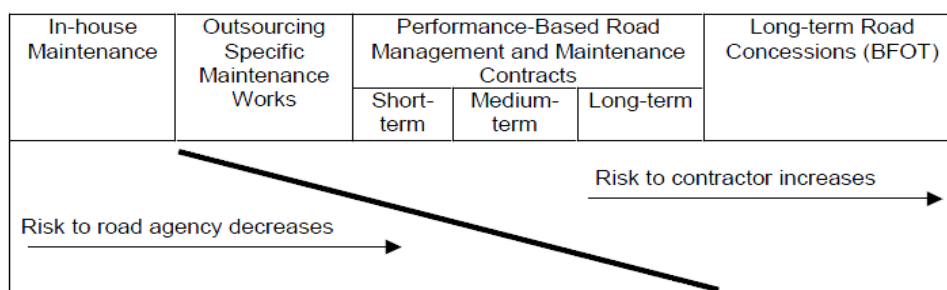


Figure 1-2: Road maintenance risk distribution for different contract forms (Zietlow, 2004)

2. PBRMC reduces the overall maintenance cost through the economy of scale. In addition, it secured a long-term funding for maintenance programs.
3. PBRMC introduces the concept of performance risk sharing through the P/I system introduced in the contract.
4. PBRMC expands the role of the private sector through introducing a new area of work where; the road maintenance was always the public sector role. This created an advantage for the maintenance contractors to innovate in order to meet the agreed service quality measures and increase his profit. This also initiates the essential need of a good management capacity for the maintenance contractor.
5. PBRMC increases the efficiency and effectiveness of road maintenance operations, through the upper hand opportunity of the employer to define strict KPIs', to ensure meeting the agreed service quality and increase the end-user satisfaction (LOS) respectively.
6. PBRMC provides the highway agencies with a better budget certainty, as the monthly maintenance expenses are pre-defined in the contract.

1.2.2 Highway Asset Management “Pavement Management System”

Highway asset management is “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” (OCED, 2001). In more specific words, Highway asset management is a tool or process to optimally operate and maintain the pavement with the minimal economic resources and achieve the public expectation, represented in the service quality. As a result, this moves us to creating an intelligent Pavement Management System (PMS) where; PMS consists of a set of coordinated activities with an objective of achieving the optimum service quality possible for the available financial resources.

PMS could be tackled from two different perspective; the project-level (micro-level) perspective, the network-level (macro-level) perspective.

1. Project-level perspective: It is managing one pavement system at a time with an objective of meeting the service quality of this certain pavement through the selection of the maintenance/rehabilitation (M&R) actions at the optimum time.
2. Network-level perspective: It is managing a network of pavements in a city with an objective of maximizing the overall network condition with limited financial resources.

PMS is “the process of planning the network M&R with an objective of optimizing the pavement conditions over the network.” (OCED, 2001) In other words, it is minimizing the network LCC, through varying the M&R action plan, with a desired pavement condition within a defined analysis period.

Besides, PMS has been clearly defined by well-known agencies and people. According to the American Association of State Highway and Transportation Officials (AASHTO, 2001), PMS is “designed to provide objective information and

useful data for analysis so that highway managers can make more consistent, cost-effective and defensible decisions related to the preservation of a pavement network” (AASHTO, 2001). FHWA (1989) defined the PMS as “A set of tools or methods that can assist decision-makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in serviceable conditions” (FHWA, 1989). To sum-up, PMS is a tool that supports asset managers to maintain the pavement and/or network condition efficiently at the least cost and the highest LOS.

The project-level PMS and the network-level PMS should be integrated together to guarantee a proper network condition. Thus, in this study, a detailed study about both the project-level and the network-level PMS will be conducted throughout the next chapters.

1.3 Problem Statement

Cairo city, as many other cities in Egypt, is facing a great challenge in dealing with an aging infrastructure. Particularly pavements, it is sought that many pavements were constructed since 30 to 40 years ago and they are nearly approaching the end of their service economic life. Apparently, based on some meetings conducted with several experts inside and outside the General Authority for Roads, Bridges and Land Transport (GARBLT), It was realized that the key threats for the existing Egyptian pavements are as shown in Table 1-1.

Table 1-1: Key threats for the existing Egyptian pavements

ID #	Threat	Threat Description
1	Increase rate of deterioration	It was apparent, based on the existing pavement’s condition; that pavements are deteriorating faster than what was expected. Generally, pavement deterioration occurs due to aging, overuse (truck overloading), misuse, and/or improper pavement management.

ID #	Threat	Threat Description
2	Vehicles overloading	There is no legal commitment with the maximum allowable loading for the pavements, which caused dramatically high increase in the deterioration rate.
3	Rapid growth in traffic	A huge increase in the vehicle ownership totaling 2,659,545 vehicle from 2005 until 2011. This resulted in more traffic loads compared to the already designed loads, which resulted in the rapid pavement structural deterioration.
4	Improper design and construction	The maintenance contractors tended to increase their profit through using less construction materials and improper compaction. Besides, the un-planned traffic growth influenced the pavement structural condition as well.
5	Poor maintenance plan	As per the meetings handled with GARBLT representatives, they stated that poor maintenance planning (optimal maintenance time, strategy and quality) for the existing pavements was one of the key threats that influenced the pavement condition.
6	Limited resources	As per the meetings handled with GARBLT representatives, they stated that limited inspection resources (cars for measuring the International Roughness Index, etc...), maintenance equipment and materials to cover Cairo pavements, and shortage of financial resources (maintenance budget) are another threats in the pavement's management.
7	Shortage of sufficient information for decision-making.	The shortage of information for the existing pavements in addition to the above-mentioned threats made it difficult for making any critical decision for pavement maintenance.

ID #	Threat	Threat Description
8	Absence of inspection control program	Another key issue was the huge difference between the inspection sheets and condition rating due to human interaction. Some inspection translation was erroneous which results in a flawed figure for the pavement condition and misleading decision-makers from taking correct decisions.
9	In-efficient current traditional PMS	The absence of an efficient PMS, in addition to the lack of information and the erroneous pavements conditions, made it even harsher for decision-makers to take the correct decision.

Generally, pavements undergo the deterioration process just on time of being opened to traffic. This deterioration process begins very slow, under the effect of traffic and other climatic and environmental condition, with imperceptible effect. Overtime, the process gets faster and faster with an urgent need of maintenance. The maintenance timing is vital decision that should be taken at the right time to maximize the rate of return from this pavement. In case of timely maintenance ignorance, the maintenance need will become higher and higher as it experiences further deterioration. Additionally, Hass et al. (1994) stated that the maintenance cost for a pavement in a very poor state condition is four to five times if a pavement is in a good state condition.

Highway agencies should think in a pro-active way by applying preventive maintenance rather than being re-active through corrective maintenance. In most countries, pavement agencies depend only on the visual inspection (corrective maintenance) to determine the need for maintenance. Because of this wrong practice, the pavement maintenance plan will be inefficient and will lead to higher maintenance budget. For instance, Al-Mansour and Sinha (1994) study showed that 25% cost saving could be achieved by applying preventative maintenance rather than corrective maintenance. They also showed that techniques that are based on the worst-first or spot repair are not appropriate as:

1. There were huge errors in the pavement evaluation.
2. Improper investigation for the distresses triggers resulted in un-suitable maintenance actions.
3. The un-suitable maintenance actions applied led to inadequate maintenance funds allocation.

1.4 Research Scope and Objectives

This research aims to develop a fully integrated Highway Asset Management System (IHAMS), which combines the aspects of a project-level and network-level PMS with a GIS system from one angle and PBRMC through the KPIs' from the other angle. This will give the highway agencies the full opportunity to perform tasks better, more economically, effectively and with higher LOS quality.

This research will be focusing on the Egyptian pavements as an application case study. Consequently, this research will be directed towards achieving the following objectives:

1. Develop an integrated project-level PMS that is capable of obtaining the optimum M&R action plan, taking the PBRMC pre-defined P/I system into consideration, to minimize the highway LCC.
2. Determine the most appropriate PBRMC KPIs' allowable limits and P/I system in order to guarantee an acceptable M&R annual expenses and thus meet the highway annual budget.
3. Develop an integrated network-level PMS that is capable of reaching the optimum M&R action plan for a highway network, consisting of different highways with different PBRMC KPIs' allowable limits and P/I systems, with an objective of minimizing the LCC and meeting the network constraints (budget and overall condition).
4. Develop a GIS model, which acts a spatial visualization tool for the highway/network to alert the highway agencies/maintenance contractors if any KPIs' deviations took place, and improve the efficiency of expenditures while achieving an acceptable highway/network condition.

1.5 Research Motivation

This research is therefore motivated by the need for a dynamic integrated system that combines the PBRMC, PMS and GIS. As concluded from the problem statement, the deficiency in allocating the limited financial resources in addition to the extremely poor existing condition initiated the urgent need of an integrated system that achieves the LOS quality and meets the limited budget constraint.

Several discussions were performed with both in-house GARBLT engineers and out-house maintenance contractors. Both shared the same conceptual overview. The first batch of internal in-house engineers proposed that there is a need for private sector interference in the next stage due to the very limited governmental resources, which act as a barrier for GARBLT to meet the minimal LOS quality. The second batch of outside maintenance contractors were willing to enhance better LOS quality for the existing highway and suggested that GARBLT should apply any contract type with proper KPIs' and P/I system as well to give them the opportunity to improve the existing LOS quality.

Numerous trials from GARBLT to introduce PBRMC took place in the last couple of years, but hopelessly, there was extremely low potential for the maintenance contractors to apply for them. As a result, several interviews with GARBLT senior managers were conducted to understand the main issue for the non-interference of maintenance contractors. Based on these interview, It was concluded that the excessive P/I system forced the maintenance contractors to put high contingency values resulting in a three to four time higher maintenance monthly value. In addition, they added that the lack of accurate system that could assess the maintenance contractor performance was the main reason why they introduced these excessive P/I values. Therefore, it is apparent that there is a need for a PMS system that integrates both the pre-agreed KPIs', for assessing the maintenance contractors' performance, and GIS that visualizes the key attributes for each segment, from a project-level perspective, and highway from a network-level perspective.

1.6 Research Methodology

In order to achieve the aforementioned objectives, the author has conducted an extensive and detailed literature review on the following:

1. PBRMC and the vital KPIs' for the maintenance contractor assessment.
2. Existing P/I systems applied for PBRMC.
3. PMS main components (asset inventory, asset Inspection, pavement condition rating systems, pavement distresses, pavement deterioration models, future prediction deterioration models, pavement M&R strategies).
4. Optimization algorithms application on PMS.

Actually, this intensive literature review helped the author to investigate the existing systems, their strength and development points, and identify the area where to intervene with the aim of improving the overall system's efficiency. This was followed by:

1. Defining adequate KPIs' and P/I system that should be applied on the intended highways under study.
2. Developing an asset inventory, which includes the most important aspects that need to be considered in the pavement study.
3. Developing an inspection program that selects the optimal inspection percentage to guarantee a proper CI.
4. Developing a future deterioration prediction model to forecast the condition at any point of time and reflect the future applied maintenance on the pavement condition.
5. Designing a GIS model to aid decision-makers (asset managers) in the budget allocation process.

1.7 Thesis Organization

This thesis consists of six chapters. Chapter 1 - Introduction introduces the research study. In addition, it delivers a generic overview of the thesis problem, scope and objectives. Moreover, it explains the methodology in which the research was conducted. Chapter 2 – Literature Review provides an extensive literature review that covers the PBRMC, PMS components, and optimization engines. Chapter 3 – Research Methodology explains the research methodology and the integration spirit between the research themes. Chapter 4 – Research Framework enlightens the proposed research framework that could be applied by the highway agencies to better perform tasks with a more economically, effectively manner and reach higher LOS quality. Chapter 5 – Validation and Verification applies validation case studies, for both the project-level and the network-level perspectives, in order to illustrate the proposed frameworks for both perspectives. Moreover, it summarizes and analyzes the results obtained from the applied case studies. Finally, Chapter 6 – Conclusion and Future Research Recommendations highlights the summary, conclusions, limitations, and recommendations of this research.



Figure 1-3: Thesis organization

2 CHAPTER 2 - LITERATURE REVIEW

This chapter introduces a general view about the different systems namely; PBRMC, PMS with its different components (inventory, inspection, condition rating, future deterioration, maintenance), and different optimization engines with an intensive focus on genetic algorithms (GAs'). Towards the end, the drawbacks of each system solely will be highlighted and the need for integrating these systems together will be pinpointed.

2.1 Introduction

In this chapter, several topics will be introduced and discussed in details as the study integrates three systems together to improve the infrastructure asset management efficiency for the highways generally and pavements particularly. The key topics, in which the chapter will focus on, could be divided into four main sections as follows:

1. Performance-Based Road Maintenance Contracts (PBRMC)
2. Pavement Management System (PMS)
3. Optimization Engine
4. Conclusions

2.2 Performance-Based Road Maintenance Contracts - PBRMC

This section will discuss the PBRMC in depth, where it will firstly begin with a general outline and a historical review about the PBRMC. Then, it will talk about its' most important aspects to guarantee a proper application. Thenceforward, it will deliberate the strength and development areas for PBRMC. Finally, a generic summary about PBRMC and its relationship with this study will be emphasized.

2.2.1 Introduction

PBRMC is “a type of contracts that focus on the outputs, quality, and outcome of the service provision and may tie at least a portion of a maintenance contractors’ payment as well as any contract extension or renewal to their achievement.” (Martin, 2003). In other words, PBRMC is “a type of contract under which the maintenance contractor undertakes to plan, program, design, and implement maintenance activities in order to achieve specified short and long term road condition standards for a fixed price, subject to specified risk allocation” (Frost & Lithgow, 1998). Simply, PBRMC sets forth the final expected road performance rather than directing the maintenance contractor with the methods and materials to achieve that expected performance. Before the PBRMC development, there were three types of specifications used in the highway construction and maintenance contracts (Ozbek, 2004):

1. Methods based specifications: In this type, the contract exactly defines the exact construction and maintenance methods and sequence in either constructing or maintaining the road. As a result, the maintenance contractor should be just performing the job as specified in the contract and is deemed to be fulfilling the contract obligations only if it follows the pre-defined method and sequence of work.
2. Material properties based specifications: In this type, the contract identifies a number of properties in which the pavement should meet. The maintenance contractor is said to be in compliance if the pre-defined properties are met independent of the construction/maintenance method used to meet the properties.
3. Method and material properties based specifications: This type of contract combines and integrates the two above-mentioned types where; the contract specifies both the method and materials to be used in order to reach the optimal performance and apply the best maintenance strategies.

It is apparent that the main aim of applying these kinds of contracts was to “provide a roadway that will carry traffic over a long service life” (Stephens et al., 1998). However, these contract types never clearly state that “the roadway needs to

provide a long and useful service life” (Ozbek, 2004). They just mentioned the quality of each element solely without correlating them to the overall performance of the pavement under maintenance. Accordingly, PBRMC assess the maintenance contractors in terms of performance not in terms of level of exerted efforts. It clearly defines a SMART KPIs’ to assess the maintenance contractor based on them.

2.2.2 Historical review about PBRMC

This section aims to provide a historical overview about the PBRMC and the main issues that should be considered before and within the contract duration. Before focusing on the PBRMC, which is a key system in this research, it is essential to understand the worldwide development stages of performance based contracts (PBC). Firstly, the concept of PBC dates back to the second half of the 1970s by the department of defense in the air force (Ozbek, 2004). Throughout 20 years of struggling, the Office of Federal Procurement Policy (OFPP) issued a number of pamphlets, guides and best practices for PBC (OFPP, 1998). Because of these efforts, many government agencies in the US started to convert their contracts to PBC under a pilot project. These agencies reported an average of 15 percent reduction in the contract price and an 18 percent improvement in satisfaction with the maintenance contractors’ performance. Moreover, the agencies added that this price reduction and customer satisfaction took place at several areas from the non-technical, technical, and professional services (OFPP, 1998). In addition, Zietlow (2004) declared that a cost reduction between 10 percent and 20 percent took place in Australia, United States, and New Zealand after the application of PBRMC. Table 2-1 shows the cost savings of different countries under PBC over the conventional contracts (Stankevich et al., 2009).

Table 2-1: Cost Savings of different countries under PBRMC over the conventional Traditional Contracts (Stankevich et al., 2009)

Country Cost savings, %	Cost Savings (%)
Norway About 20-40%	About 20% - 40%
Sweden	About 30%
Finland	About 30% - 35%; about 50% less cost/km
Holland	About 30% - 40%
Estonia	20% - 40%
England	10% minimum
Australia	10% - 40%
New Zealand	20% - 30%
USA	10% - 15%
Ontario, Canada	About 10%
Alberta, Canada	About 20%
British Columbia, Canada	Some of might be in the order of 10%

As discussed above, the high tendency towards PBC was showing itself in the area of transportation. From here, the term PBRMC fell under the generic term of PBC. PBRMC has been successfully applied by the transportation agencies of many developing and developed countries such as Canada (1988), Argentina (1990), Australia (1995), USA (1996), Uruguay (1995), Chile (1997), New Zealand – Columbia – Brazil – Finland (1998), and Zambia (1999) (Zietlow, 2004).

Moving on to the two key aspects that need to be concerned about before applying PBRMC. One of the most important decisions that should be carefully taken by the transportation agencies is the determination of the contract period and the pilot project length. Zietlow (2004) stated that the PBRMC contract periods and pilot project length vary from country to country according to different factors. Examples of the different factors affecting the contract period are the road administration's experience with contracting out road maintenance and the local maintenance contractors' performance in applying new technologies to maintain the required condition. The longer the road administration gained experience of contracting out the road maintenance, the more comprehensive the approach will be implemented. For instance, Guatemala and Honduras (2002) had executed the road maintenance by in-house staff using one or two-year performance-based contracts with KPIs' related to the routine maintenance only. Other examples can be Brazil, Chile, and Uruguay where; Brazil started applying performance-based contracts with 3 to 5 years contract

duration and a 300 kilometers pilot project (network), concerned mainly with the asphalt concrete roads and bituminous treated surfaces only. In addition, it is necessary to consider it from both legal and financial perceptions. For instance, In Latin America, the maximum contract period defined legally is five years. As a result, to go for long-term contracts, you have to change the laws (Zietlow, 2004).

Additionally, Sultana et al. (2012) introduced seven main issues that should be considered by the transportation agencies before applying PBRMC as shown in Figure 2-1.

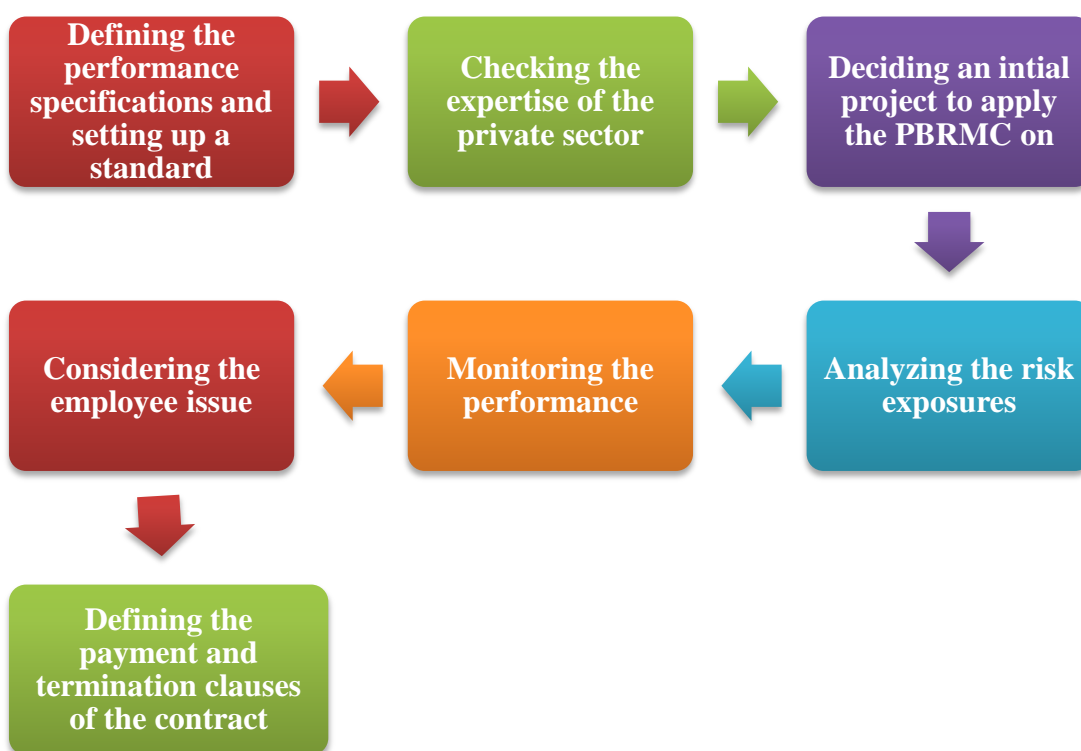


Figure 2-1: The seven main issues before applying PBRMC (Sultana et al., 2012)

As shown in Figure 2-1, the first issue is the transportation agency obligation to define the performance specifications and set-up a standard for these performance measures. Then, the agency should check the private sector capability of handling the road maintenance to reach the desired LOS quality. After that, the implementation stage takes place where; an initial project has to be decided for the performance-based

contracts to be applied on. A detailed risk analysis has to be done in order to define the events that are out of the maintenance contractors' control and share those risks with the maintenance contractor. Hence, the performance monitoring process takes place where; the maintenance contractors are evaluated according to their performance within the contract period. In order to assess the maintenance contractors' performance, De la Garza et al. (2009) hosted the key five components for monitoring PBRMC and their direct relationship with the overall performance as shown in Figure 2-2.

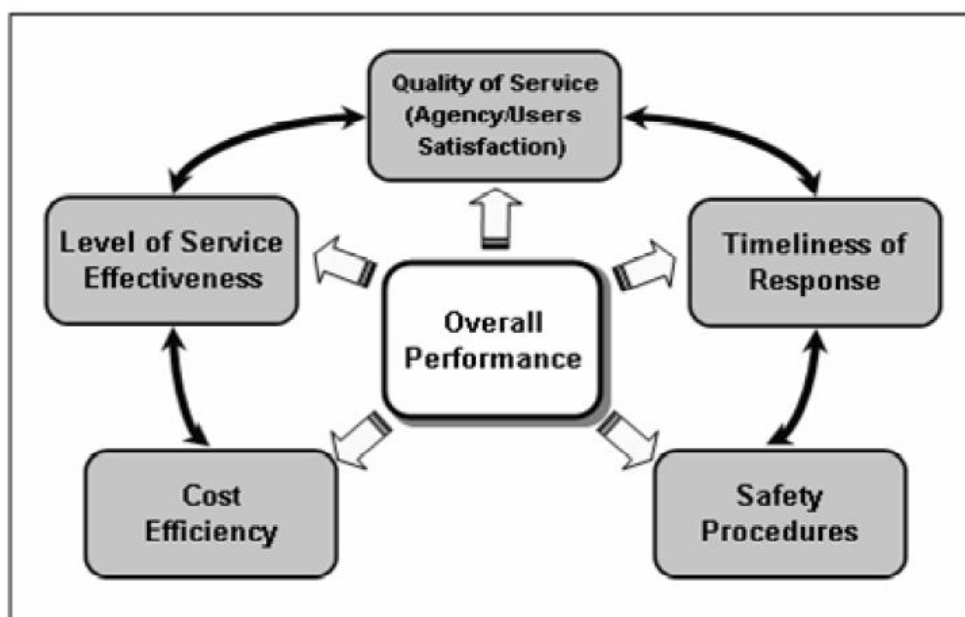


Figure 2-2: The five components for monitoring the PBRMC (De la Garza et al., 2009)

As shown in Figure 2-2, the five main components for monitoring the PBRMC are the LOS effectiveness, timeless of response (TOR), safety procedures (SP), quality of service (QOS), and cost-efficiency (CE) (De la Garza et al., 2009). De la Garza et al. (2009) highlighted the methodology for each component to be evaluated under the PBRMC. A brief description for each component is as follows:

1. LOS effectiveness indicates the extent to which the maintenance contractor is meeting the performance criteria and performance targets, defined in the contract, throughout the contract period.

2. TOR evaluates the response time of the maintenance contractor to service requests related to events or deficient elements in the roadway that need to be attended to in a timely manner.
3. SP checks that the maintenance contractor is properly implementing a safety program. It also ensures that the road users as well as the maintenance crews performing the work are exposed to minimum risk of accidents.
4. QOS evaluates the customer perceptions with respect to the condition of the assets and maintenance contractors' performance. Customers are the ultimate evaluators of the quality of service provided; therefore, it is extremely important to assess their satisfaction.
5. CE assesses the cost savings accrued by the government because of engaging a maintenance contractor to perform the road maintenance services.

The sixth issue, to be considered before applying the PBRMC, is the employee issues where; due to the huge implementation of PBRMC, the national and sub-national highway agencies workforce had declined. In Estonia, 63% of the national road network is under PBRMC, the national highway agency work force declined from 2046 employees in 1999 (561 administration staff and 1485 workers) to 692 employees (343 administration staff and 349 workers) in 2003. Sultana (2012) suggested that the transportation agencies should consider the employee issue before introducing PBRMC. Moreover, transportation agencies should prepare a plan for the lost staff to guarantee the success of the PBRMC. Finally, the seventh step is the proper definition of the payment and termination clauses in the contract to avoid any conflicts or disputes that may arise during the contract period (Sultana et al., 2012).

Moving on to the risks in the PBRMC, the maintenance contractor is limited to the risk of defining all the project requirements, excluding the unknown conditions. The highway agencies are moving from the traditional type of contracting to Long-term PBRMC, to decrease their own risks and increase the risks on the maintenance contractors (Queiroz, 1999). Figure 2-3 shows the risk distribution with different

contractual approaches. However, it is worth to illustrate the variance in risk allocation under PBRMC in different countries (Segal et al., 2003):

- In Virginia, U.S.A., the risk of unpredictable costs, including inflation, escalating materials prices, accidents, etc. were carried out by the maintenance contractor.
- In Argentina, the maintenance contractor was reimbursed for any cost overruns taking place due to any risk beyond his control such as; earthquakes, hurricanes, and materials shortage. However, they used the schedules of rates defined in the contract documents as a baseline for overruns calculation. The risk of excessive costs overruns is contained by 25% cushion on these prices.
- In England, Columbia, Canada, and Estonia, PBRMC included an annual price adjustment process that considers any changes in labor and fuel prices indices.

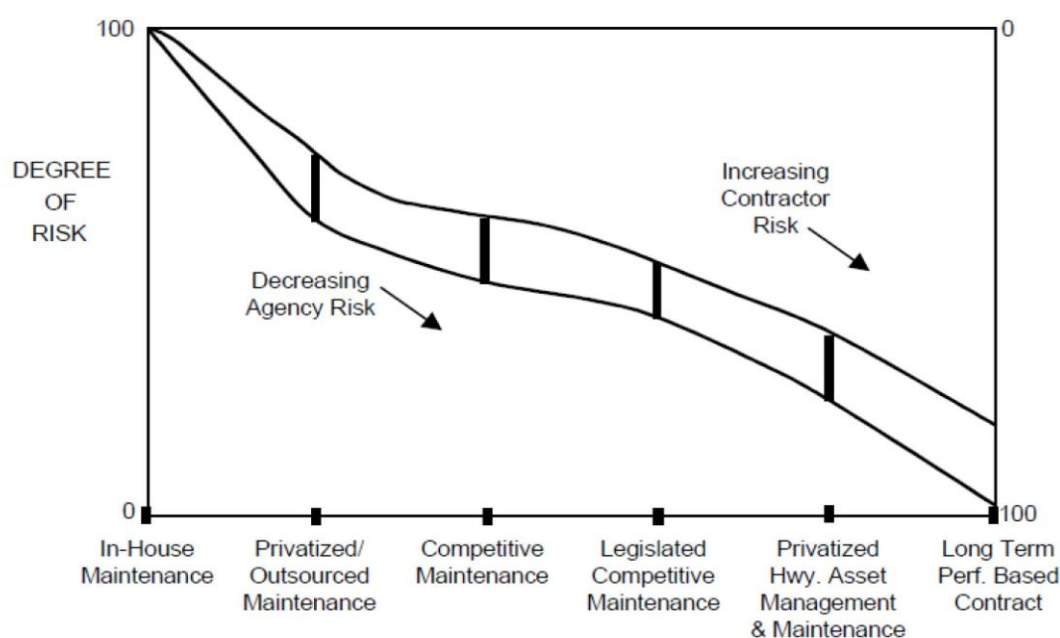


Figure 2-3: Risk Distribution with Different Contract Approaches (Haas et al., 2001)

2.2.3 KPIs' and P/I system for PBRMC

This section aims to provide an overview on the different KPIs' and P/I systems introduced by researchers and/or applied past projects and case studies in order to gain a wide-ranging knowledge about the different existing systems. As an example, Cabana, et al. (1999) introduced the "CREMA System" (Contrato de Recuperacion y Mantenimiento), which was implemented in Argentina covering 12,000 Kilometers (i.e. approximately 40% of the national paved road network). This contract was applied over a 5-year period where; it comprised the M&R works of 200 to 300 kilometers long sub-networks. Moreover, they presented a framework for the CREMA concept where; they showed the different types of works included in the system, the contractual clauses, and the system features. Table 2-2 highlights the KPIs' defined in the contract and the penalties associated in case of not meeting either the KPI limit or the desired response time. Finally, they mentioned that, by applying the CREMA system in long terms, a reduction in the maintenance operational costs occurred with an extremely great improvement in the quality and cost-effectiveness of the maintenance operations.

Table 2-2: Penalties for non-compliance with mandatory CREMA requirements in Argentina, 2004 – 2005 (Stankevich et al., 2009)

Section	Parameter	Performance Requirements	USD equivalent
Subject to rehabilitation	Pavement Roughness	IRI max.=3 (AC) IRI max.=3.5 (S.T./RC)	250/week/km
	Pavement Rut Depth	1 cm max.	500/week/km
	Pavement Edge Break	0 cm	500/week/sector
	Pothole>2.5 cm	100% patched	500/day/pothole
	Cracking	100% sealed, and < 15% type 2 or 4	250/week/km
	Concrete pavement joint cracks	100% sealed	250/week/km
	Ravelling	0%, and <2% if surface treatment	250/week/km
	Subject to Routine Maintenance	Edge Break	3 cm max
Cracking		100% sealed up to type 4	250/week/km
Pothole		100% patched	500/day/pothole
Ravelling		100% patched	250/week/km
Paved Shoulders		Pothole/raveling=0 Edge break=0 Rutting<12 mm Cracks sealed up to type 4	500/week/km
Unpaved Shoulders		No erosion, no rut, good transversal slope; edge break<2 cm; width>=3 m.	500/week/km
Bush Clearing		Bush height<15 cm over 15 m	50/ha/week
Culvert/drains/bridge cleaning		Clean/Unobstructed	250/day/km
Cleaning of Right-of-Way		No debris; maintain green areas	250/day/km
Vertical Signs		Well maintained and visible day and night	50/day/sign
Lighting		Well maintained	50/day/light
Horizontal Marking	Well maintained and visible day and night	100/day/line/km	
Guardrails	In good condition	500/week/location	
Notes:			
<ol style="list-style-type: none"> 1. Penalty application are waived during initial 3 months of contract, generally; 2. Roughness on sections subject to routine maintenance is measured for indicative purposes only; 3. 10% of the contracted network has to be inspected every month, by individual segments of 2 km; 4. Reduction of original thickness of wearing course not allowed; 5. Milling of rut allowed only if material milled is replaced; 6. Surface treatment over Asphalt concrete not allowed; 7. When crack type > 4, sealing may be replaced by other treatment (ex: slurry seal, micro-asphalt); 8. One month routine maintenance = USD 200/month*200 km= USD 40,000/month, on average per network; 9. Ex: 1 pothole remaining open every 10 km during one week = 500*7 days*200/10 km = USD 70,000 penalty; 10. 4 horizontal marking lines missing over 10 km during 1 week = 4*100*7*10=USD 28,000 penalty; 11. More than half of the above penalty parameters related to road safety concerns (risk of accidents) 			

Alternatively, a report prepared by Autostrads (1999) stated that contractual KPIs' do not only measure the asset physical condition, but they also expand to include broader non-technical measures. Figure 2-4 shows a sample of 12 KPIs' defined in this study and considered as "Non-Technical Performance Measures" (Autostrads, 1999).

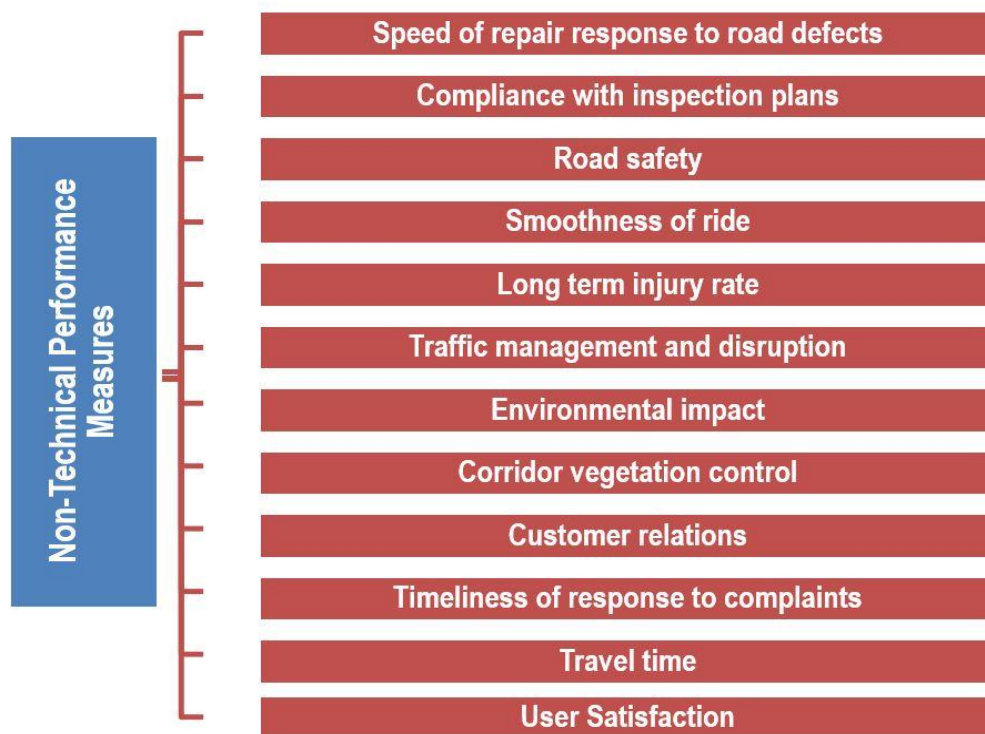


Figure 2-4: Non-Technical performance measures (Autostrads, 1999)

In addition, Horak et al. (2001) introduced another example for PBRMC where; they explained the road KPIs' from a different perspective. They defined the KPIs' as "indicators designed to be objective measures of performance for a road authority". Moreover, they added that the main three aspects to be addressed in the asset management KPIs for roads are as follows:

1. Performance (e.g. measuring skid resistance, rutting, texture, and roughness)
2. Visual appearance (e.g. number of defects, degree of defects and extent of defects)
3. Structural (e.g. calculation of the remaining life – Deterioration rate)

Furthermore, they explained the South African Road Agency Ltd (SANRAL) approach, which was firstly introduced by Kannemeyer (2000). SANRAL discussed the financial method to determine the replacement value using different depreciation types, depending on the structural deterioration rate, over the pavement life as shown in Figure 2-5. They realized that the roadbed has a different useful life than the pavement layers, which results in a higher asset value in the future due to the inflation. In addition, they analyzed the relationship between the replacement value of roads and pavement life on both the pavement layers and the roadbed. Finally, they concluded that as the level of survey (method) increases, the data survey cost increases, which results in a dramatically high increase in the results confidence and a decrease in the risks associated with the results. Figure 2-6 shows this relationship between the levels of survey used, data survey cost, confidence and risk (Horak et al., 2001).

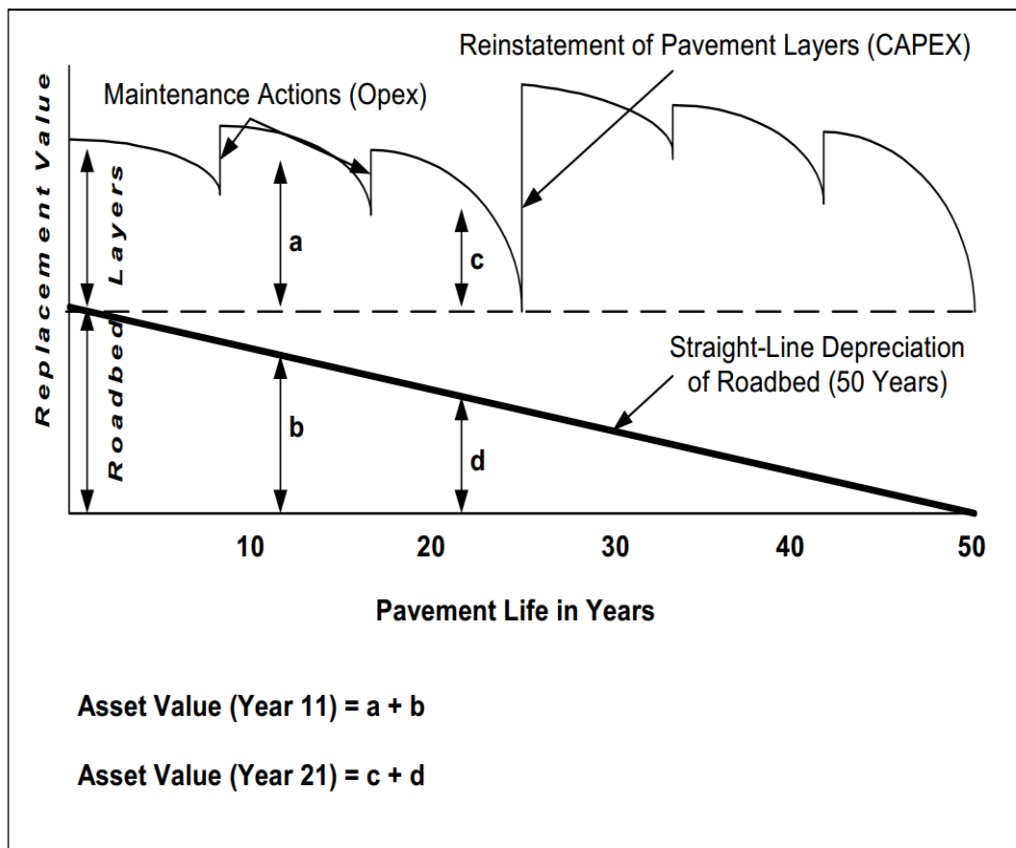


Figure 2-5: SANRAL method of road asset value calculation (Horak et al., 2001)

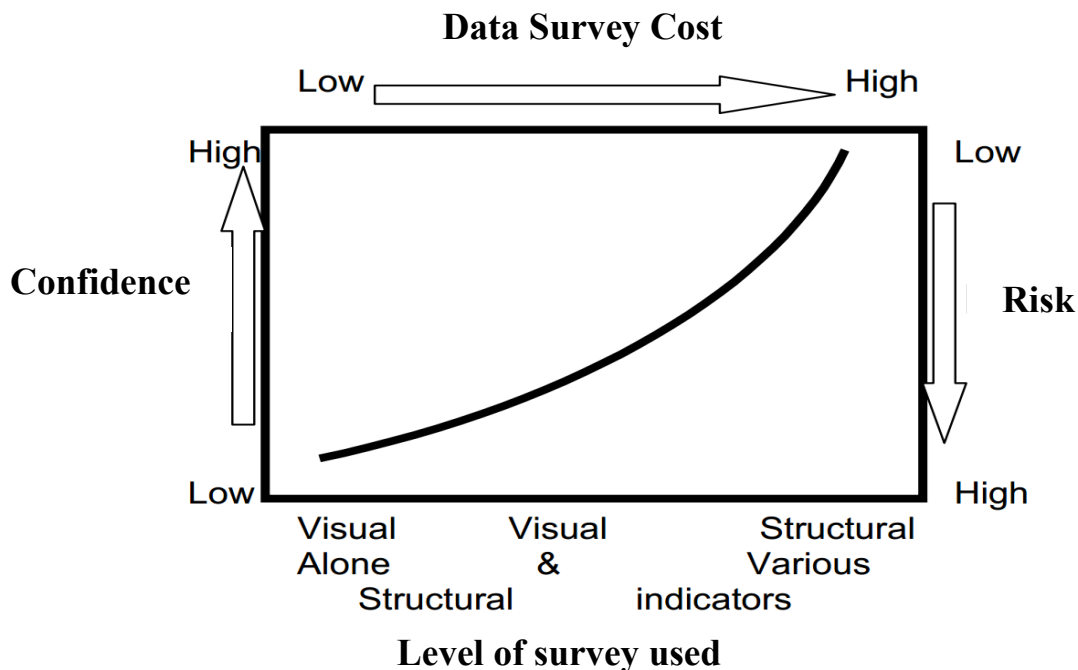


Figure 2-6: Risk, Confidence, Cost and Level of survey relationships (Horak et al., 2001)

Furthermore, Logue and Avery (1998) declared that it is necessary for the road authority, in order to warrant a high performance, to make sure that the desired road is structurally well with good appearance and without any reduction for the average remaining life. They suggested that it could be reached by applying the concept of “Fit for Purpose” as a basic descriptor of the road asset in their long term PBRMC.

In addition, The Organization for Economic Co-Operation and Development (OECD, 2001) studied the road KPIs’ and produced a detailed field study for each and every performance indicator. They also added an analysis section for each KPI where; the following six questions were asked for the road administration members’:

1. Definition of the KPI
2. Use of the KPI
3. Targets set for each KPI
4. Results for each KPI to check whether the target set was achieved or not
5. Trends for each KPI and why the target set was or wasn’t achieved

6. Best practice for each KPI

Finally, they conducted a detailed survey analysis for fifteen countries to analyze each KPI solely based on the above questionnaire. Table 2-3 shows the KPIs' introduced by the OECD and used by the fifteen-member countries as a case study in this research (OECD, 2001).

Table 2-3: KPIs' introduced by the Organization for Economic Co-operation and Development (OECD, 2001)

KPI ID #	Description
KPI 1	Average road-user costs
KPI 2	Level of satisfaction regarding travel time and its reliability and quality of road user information
KPI 3	Protected road-user risk
KPI 4	Unprotected road-user risk
KPI 5	Environmental policy/programmes
KPI 6	Processes in place for market research and customer feedback
KPI 7	Long-term programmes
KPI 8	Allocation of resources to road infrastructure
KPI 9	Quality management/audit programme
KPI 10	Forecast values of road costs vs. actual costs
KPI 11	Overhead percentage
KPI 12	Value of assets
KPI 13	Roughness
KPI 14	State of road bridges
KPI 15	Satisfaction with road condition

Likewise, Haas et al. (2009) stated that KPIs' are an essential part in the pavement asset management. The reason behind that was the crucial need for effectively allocating the limited available resources in order to improve the pavement condition and minimize the costs. Additionally, they outlined the six main objectives of defining the KPIs' as follows:

1. Assessing the pavement physical condition
2. Determining the asset value, which varies depending on the accounting base and the valuation method

3. Introducing a monitoring mechanism for assessing the policies' effectiveness and compliance with pre-defined policy objectives
4. Provision of information to users and customers
5. Introducing a resource allocation tool for comparing different alternatives
6. Diagnosing for early identification of any asset accelerated deterioration and quickly taking proper corrective action at the proper time.

2.2.4 PBRMC strength and development areas

This section aims to summarize the PBRMC strength and development areas, concluded from past researchers and/or case studies, in order to illustrate the need for an integrated system, which links the theoretical/contractual PBRMC to the real world and to the future decision-support systems. In addition, it tackles the strength point, from the roads agencies perspective, in order to show how applying such type of contract would improve the government expenditures in maintaining the pavements' network condition.

Pinero and De la Garza (2003) stated that PBRMC calls for performance-based work, in which the outcome (KPIs') are specified rather than material or method of implementation. They also added that this contracting scheme could act as an excellent tool for improving the government expenditures while maintaining an enhanced condition. On the other hand, they stressed on the essence of properly identifying the KPIs' because without proper outcome analysis, this type of contract would likely result in adverse outcomes. Another point that was also discussed in this research was the resistance to change where; the highway agencies tend to rely on past comprehensive set of guidelines to evaluate the efficiency and effectiveness of the contract resulting in improper evaluation for the maintenance contractors' performance, which by default result in inappropriate assessment (Pinero & De la garza, 2003).

Finley (1989) and Tomanelli (2003) showed that PBRMC is better than traditional maintenance contract scheme because the maintenance contractors may be aware of cheaper and better process to reach the outcome. In addition, they stressed on the case that the owner has just to identify proper KPIs' to evaluate the maintenance contractor based on. Furthermore, they indicated that the competitiveness between the maintenance contractors would create the will for each maintenance contractor to submit the least financial offer, leading the maintenance contractors to choose the optimal process that both minimizes the cost and meets the pre-defined contractual KPIs'. Finally, they pinpointed on the fact that maintenance contractors will be working in more effective manner when they have the maximum freedom to choose the process to work with throughout the contract period (Neveda Test Site (NTS), 2003).

Ozbek (2004) discussed the PBRMC from a contractual perspective where; he developed the main performance warranties for PBRMC with the aim of reducing the risk for the highway agencies and improving the future performance of PBRMC. He stated nine strength points for PBRMC over the traditional maintenance contracts, which could be, summarized as follows (Ozbek, 2004):

1. It allows the maintenance contractor to deliver the project by following his/her own best practices, as he/she is obliged to meet certain KPIs' or an end result not a certain method to follow.
2. It maximizes the maintenance contractors' innovation as the maintenance contractors' may get incentives in case of promoting any innovation throughout the contract. In addition, this may give the highway agencies the opportunity to learn these new technologies and implement them for the projects' they are carrying on by their own forces.
3. The risk is fully transferred to the party having much control over the project (maintenance contractor). As a result, the probability of failure is minimized, as the maintenance contractor will be implementing the methods and procedures that he is aware of within the contract period (Neveda Test Site (NTS), 2003).

4. It is cost effective for both parties involved in the contract. There will be a high probability of attaining saving by the highway agency through reaching the desired KPIs' and network condition with the risk transferred to the maintenance contractor. In addition, the maintenance contractor will save money through applying the optimal M&R action plan that minimizes the LCC and guarantees meeting the KPIs' Nevada Test Site (NTS), 2003).
5. It helps in building a long-term, trustworthy, and stable relationship between the highway agency and the maintenance contractor providing further opportunity for future work between both parties.
6. It minimizes the negative impact of the highway projects on the public as the highway agencies tends to define strict KPIs' on the maintenance contractor to reduce the construction time, which results in a shorter driving times through and around the work zone and thus enhance the public safety. In addition, it reduces the negative impacts of noise and pollution because of the reduced construction time introduced as a separate KPI in the contract (Carpenter et al., 2003).
7. It minimizes the inspection frequency, as there is certain KPIs' defined in the contract to evaluate the maintenance contractors' performance. On the other hand, the quality control (QC) is the maintenance contractors' responsibility, which releases the highway agency from allocating both financial and technical resources for the QC.
8. It improves the condition and LOS of the pavement due to the timely and effective maintenance activities.
9. It minimizes the administrative costs needed to be spent in bidding, administrating, and managing a huge range of short-term individual contracts. After applying PBRMC, there will be just a single contract, in which the highway agency will be dealing through, with the maintenance contractor.

On the contrary, Ozbet (2008) declared that in some cases, the maintenance contractors' innovations in materials or processes, in order to minimize the costs, could bring some undesirable consequences to the project to reach the pre-defined contractual KPIs'. Additionally, he added that the maintenance contractor's increased control over the project might reduce the pavement LOS. In addition, the responsibility of the unperformed work or the defects taking place at the end of the contract should be clearly defined in the PBRMC to avoid any vague clauses or any conflicts that may occur at the end of the contract period.

2.2.5 PBRMC conclusions

PBRMC has been successfully developed since the second half of the 1970s' (Ozbek, 2004). It has been firstly applied on roads in 1988 in Canada where; it showed cost savings around 10% - 20% (Zietlow, 2004). Moreover, it has been successfully applied in different countries, showing a cost savings between 10% and 50%. The main concern was defining proper KPIs' limits to guarantee an acceptable LOS. Additionally, the highway agencies have to develop an inspection and condition rating system in order to evaluate the maintenance contractors' performance based on the pre-developed inspection and condition rating system. After that, the study discussed the KPIs' and P/I system to assess the maintenance contractor performance throughout the contract period. Several researches were conducted on defining the best KPIs' and P/I system from a technical point of view. It was recognized that the majority of the literature conducted on the PBRMC focused on the contractual and risk management aspects of these contracts. At this point, it was obvious that there is a missing gap between the PBRMC and PMS, since the main link between both is the KPI's and P/I system. Therefore, the author decided to consider the operational aspects related to optimal performance/cost from the system operators and maintenance contractors perspective through integrating the PBRMC and PMS with an objective of analyzing the effect of KPIs' limit and P/I system on the financial status of the contract. Finally, the study deliberated the strengths and development areas in the PBRMC, based on actual case studies, from the technical, financial and workability point of views. It was apparent that PBRMC has shown a great cost savings and better pavement and/or network condition in developed and developing countries directing the countries towards an enhanced infrastructure condition with an improved efficiency of expenditures.

2.3 Pavement Management System - PMS

2.3.1 Introduction

PMS is “the process of planning the network M&R with an objective of optimizing the pavement conditions over the network.” (OCED, 2001). In other words, it is minimizing the network LCC, through varying the M&R action plan, with a desired pavement condition within a defined analysis period.

Additionally, PMS has been clearly defined by well-known agencies and researchers. According to AASHTO (2001), PMS is “designed to provide objective information and useful data for analysis so that highway managers can make more consistent, cost-effective and defensible decisions related to the preservation of a pavement network” (AASHTO, 2001). FHWA (1989) defined the PMS as “A set of tools or methods that can assist decision-makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in serviceable conditions” (FHWA, 1989). To sum-up, PMS is a tool that supports asset managers to maintain the pavement and/or network condition efficiently at the least cost and the highest LOS. Figure 2-7 shows the high effect of the PMS on the total LCC in terms of different pavement phases within the analysis period.

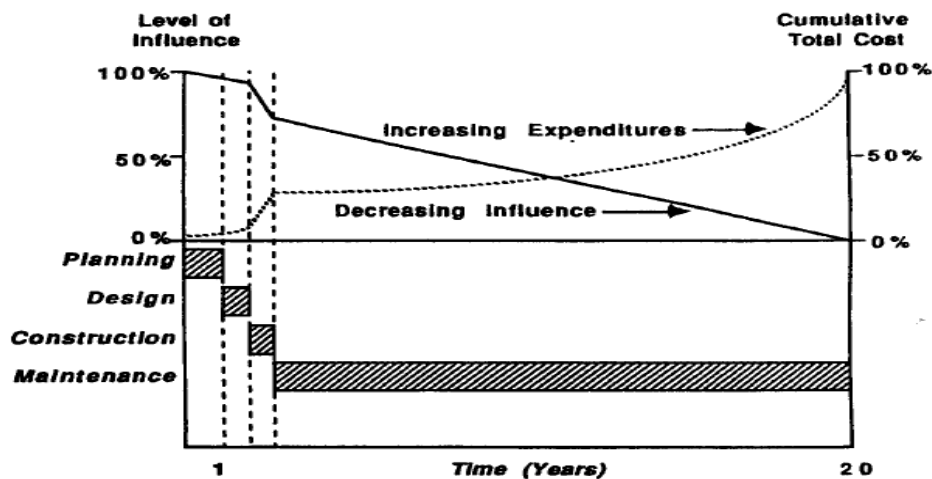


Figure 2-7: Effect of PMS on the cumulative total LCC (Haas et al., 1994)

Hass et al. (1994) believed that “Good pavement management is not business as usual, it requires an organized and systematic approach to the way we think and in the way we do day to day business. Pavement management, in its broadest sense, includes all activities involved in the planning and programming, design, construction, maintenance, and rehabilitation of the pavement portion of a public works program.” (Haas et al., 1994)

2.3.2 Historical review about PMS

This section aims to provide a historical overview about the PMS and the aim behind developing a PMS for managing the future M&R pavement expenditures. The term PMS initially started at the late 1960s’ and early 1970s’ where; it was defined as the means of describing the range of activities that are involved in providing serviceable pavements. At that time, it was based on systems engineering approach to solve the problems of economical design, construction and pavement M&R (Peterson, 1987). Since then, many highway agencies in Canada and U.S. began working on PMS. As the sophistication substantially increases, the associated PMS costs tend to increase as well (Chairul, 1991).

There are numerous numbers of PMS available in different states and countries according to their needs and usage. The World Bank (1988) prepared a detailed study discussing the causes and remedies of the road deterioration in the developing countries. In this study, the authors declared that, in the 1960s’ and 1970s’, the road networks expanded much faster than the corresponding maintenance budgets and institutional capacities. In addition, the traffic has dramatically increased in a much faster rate than what was expected, leading to an increased axle loads to exceed the designed capacity of the pavements. After a period of ten to fifteen years, the pavements continued to rapidly deteriorate causing them to break apart without conducting any timely M&R strategies. They added also that the inadequate M&R strategies in the developing countries are due to the governmental lack of planning and understanding of the problem fatality (The World Bank, 1988).

Jorn (2005) has described how the asset values are expressed in terms of monetary and non-monetary parameters. He also related the asset values with the PMS as well as the optimization algorithms. In addition, he defined the term “Minimum Cost Level” as the optimum service level that may be seen from the economically optimum point of view. Figure 2-8 shows the direct relationship between the LOS and the M&R costs (Jorn, 2005).

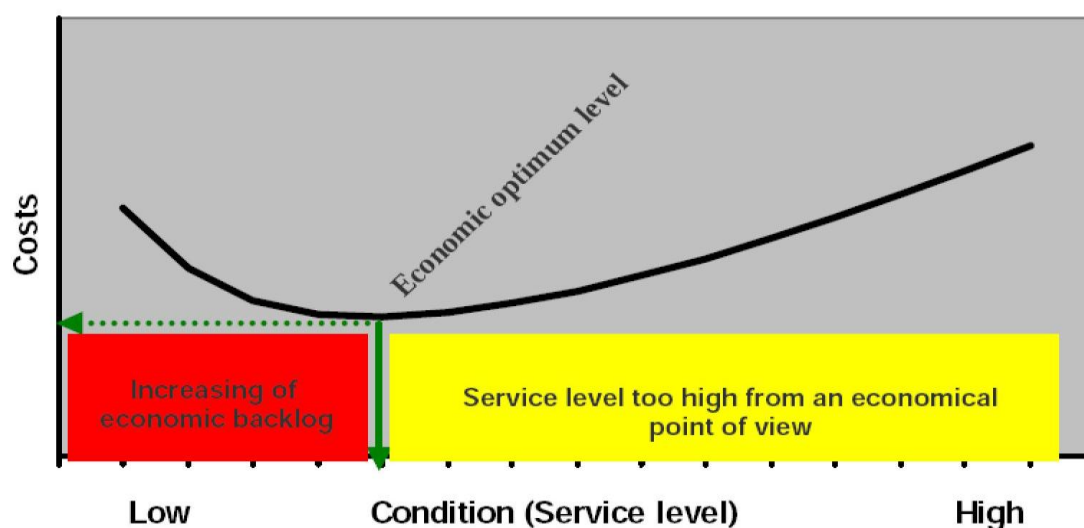


Figure 2-8: Relationship between the LOS and M&R Costs (Jorn, 2005)

Sanjiv et al. (2004) developed another example for PMS. The objective of this study was to assist the highway engineers to maintain the highway network and to support the authorities to allocate the funds, based on a cost effective criteria, concerning the M&R of the pavements. In this study, both project-level and network-level PMS were developed showing a cost savings of more than 33% for the highway agency costs over a 20 years analysis period (Sanjiv et al., 2004). In addition, the Riverside County Transportation Department (2011) presented a report that summarizes the PMS and illustrates the importance of having a PMS that guides and supports the pavement needs and priorities within the available budget. Furthermore, they defined the PMS as “a decision-making process or system that assists the county in making cost-effective decisions related to the M&R of the roadway pavements”. They added-up a condition rating system that translates the numerical pavement condition to linguistic condition states. Moreover, they developed a deterioration

model and compared the pavement service life in the two-cases in which, either applying the PMS for choosing the M&R strategies or not applying the PMS, for choosing the M&R strategies, in the decision-making process. Figure 2-9 and Figure 2-10 show the pavement deterioration curve and the comparison conducted to show the effect of either applying or not applying M&R strategies on the pavement condition state respectively (Riverside County Transportation Department, 2011).

Finally, Maher (2004) developed a full PMS for Gaza City. The objective of this research was to introduce a PMS that provides a systematic process in maintaining, upgrading, and operating the pavements to facilitate the decision-making process and better perform the tasks a much more cost effective manner. To develop this system, integration between the Micro-PAVER pavement software and GeoMedia GIS software was conducted to utilize the capabilities of each individual package. Finally, a graphical interface was developed in order to justify the decisions taken by the system (Maher, 2004). Furthermore, Fay et al. (2009) prepared a PMS study that discussed the importance of implementing a proper PMS to manage the annual M&R costs. In addition, they added a criterion for calculating the pavement condition based on a matching-eye inspection criteria. Towards the end, they performed what-if scenarios for different scenarios where; they showed the chosen scenarios' effect on the pavement condition and the annual budget (Fay et al., 2009).

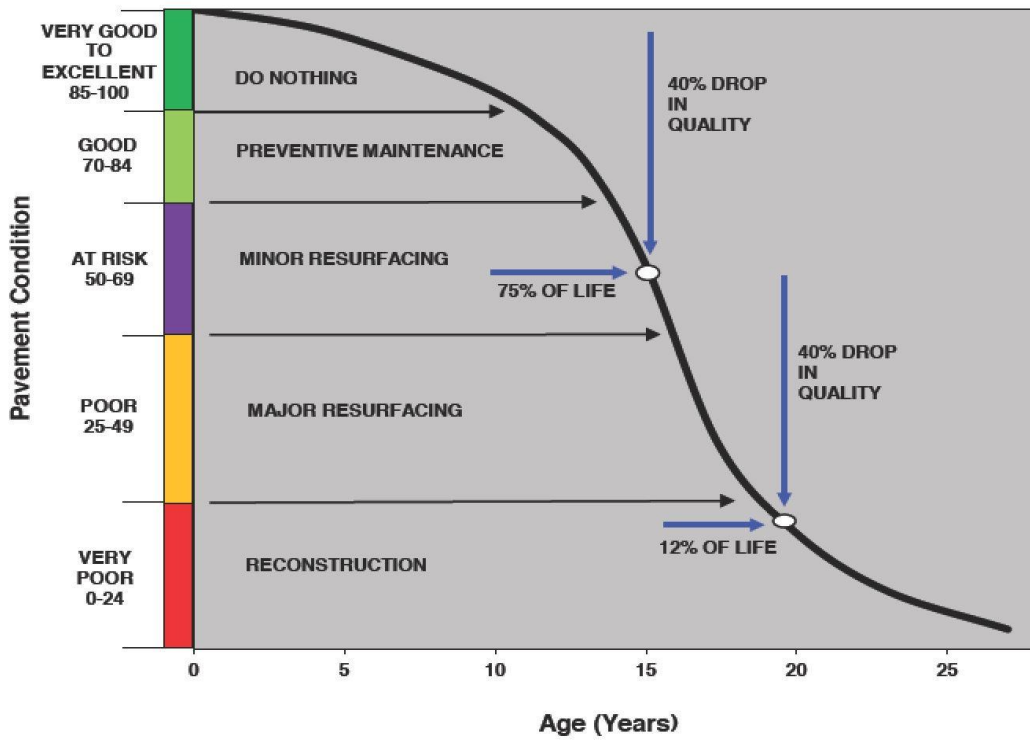


Figure 2-9: Pavement Deterioration curve (Riverside County Transportation Department, 2011)

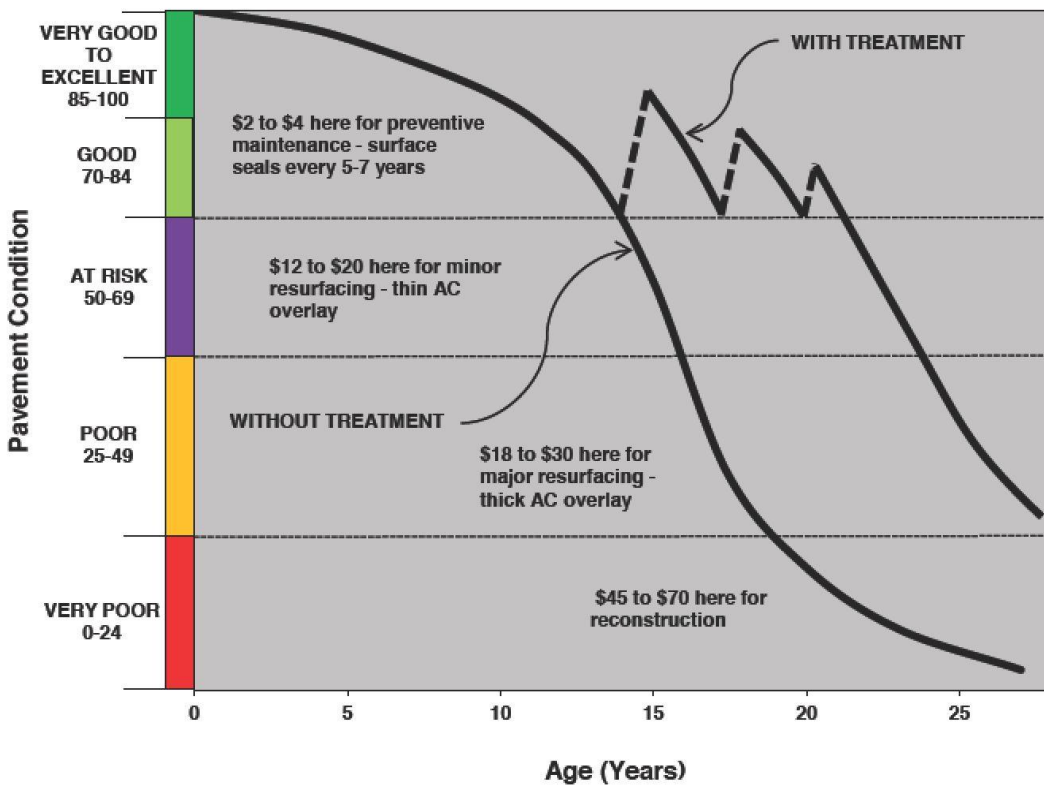


Figure 2-10: Pavement Deterioration Curve with and without M&R (Riverside County Transportation Department, 2011)

2.3.3 Pavement inventory

This section aims to provide a background about the asset inventory role in the PMS. Moreover, it aims to discuss different asset inventory manuals and examples that were developed by different institutes within different countries. A proper asset inventory is the foundation from which all the PMS decision-making support is originated (FHWA, 2003). The main purpose of the asset inventory is providing access to the needed data to reduce the duplication. Therefore, the data should be both accessible and integrated to guarantee an effective analysis for both the project-level and network-level PMS. In addition, Haas et al., (1994) stated that successful and accessible data organizing, acquiring and recording is one of the most vital activities in the PMS. Despite the fact that the focus of many PMS is the pavement surface, structural condition and LOS, asset inventory should contain data from a variety of sources (Haas et al., 1994). Accordingly, Haas (1991) defined the data categories that need to be included in the asset inventory as follows (Haas, 1991):

1. Section reference and description
2. Performance-related data
3. Historical-related data
4. Policy-related data
5. Geometry-related data
6. Environmental-related data
7. Cost-related data
8. Traffic-related data

In addition, Haas (1991) and FHWA (1990) indicated four pavement measures evaluation namely; roughness, surface distress, deflection, and surface friction. The output variables of their studies, to track the pavement condition as well as the LOS,

were these measures in addition to the M&R and user costs (Haas, 1991), (FHWA, 1990).

Attributable to the expansive variety of data required to guarantee an efficient PMS, many highway agencies maintain the data sets separately. Those separate data files are performed for the different categories. No matter what the data type stored in the dataset is, there should be integrity, accuracy, validity, security, and proper documentation (FHWA, 1990):

Mubaraki (2010) upheld that a proper asset inventory system should contain the following files:

1. Condition rating file
2. Distress measurement criteria file
3. Traffic level containing the Average Annual Daily Traffic (AADT)
4. Highways and a history file that contains the construction history of all pavement
5. Maintenance history files containing M&R activities and cost

A numerous number of comprehensive asset inventories has been developed within the last 15 years. Arizona Department of Transportation (ADOT) (2006) has developed a comprehensive asset inventory, which functions through three datasets namely; the pavement management dataset, the pavement construction history dataset, and pavement deflection dataset. Firstly, the pavement management dataset contains information about the route identification, traffic level, traffic growth rate, maintenance cost, and pavement condition data. In addition, it includes cracking, roughness, and skid measurements annual data. Moving on to the pavement construction history dataset, which contains records for the location, type of material and thickness of each pavement layer for each construction project), concerning each project that has been executed by the department. Finally, the pavement deflection dataset, which contains records of all the data collected about the pavement deflection testing (ADOT, 2001).

Moreover, the Southern Tier East Regional Planning Development Board (2010) developed an asset inventory guide to summarize the New York State Department of Transportation (NYSDOT) guidelines. In this guide, the asset inventory was divided into five categories as follows (Southern Tier East Regional Planning Development Board, 2010):

1. Location/Identification Dataset: It contains information about the location identity, which includes the route number, qualifier, county name, region county number, primary end mile point, reverse BMP, end reference marker, and State Highway (SH) number.
2. Physical Characteristics Dataset: It contains information about the highway physical characteristics, which includes the segment length, total number of lanes, roadways, paved shoulder width, roadside type, pavement width, pavement type, sub-base, and functional class.
3. Traffic Records Dataset: It contains data about the traffic records, which includes AADT, percentage trucks, and V/C Ratio.
4. Condition Information Dataset: It contains information about the pavement condition, which includes surface rating, ride quality data – International Roughness Index (IRI), pavement rut depth, pavement average bump height, number of bumps, dominant distress, and pavement condition.
5. Maintenance Works Dataset: It contains information about the previous M&R works executed in a certain segment, which includes year last crack sealing, year last work, and work type.

The distresses dataset category was considered solely as there are a huge number of distresses identification manuals that were developed by different institutions in different countries. FHWA (2003) developed a distress identification manual for the U.S. Department of Transportation. In this manual, each distress was defined through some main attributes as follows (FHWA, 2003):

1. Distress type
2. Detailed description with the triggers that initiated this distress
3. Distress units of measurements

4. Distress severity levels
5. Distress measurement criteria (Equipment if needed)

Another manual was developed by the transportation information center (2002) to assist local officials in understanding the pavement surface condition. In this manual, each distress was defined and the severity levels for each distress were illustrated using digital photos. Additionally, they added a separate section that aids the maintenance contractors in the decision-making process, based on the resulting surface rating (Transportation Information Center, 2002).

Finally, GARBLT (2011) developed a distresses identification manual for the asphalt pavements. In this manual, each distress was defined with a detailed description and illustrative digital photos for the distress. Then, the severity levels and the measurement criteria are defined. After that, the reasons behind the distress occurrence are stated. At the end, a descriptive table that indicates the best M&R strategy for different severity and extent level of each distress is outlined for evaluation purposes (GARBLT, 2011).

2.3.4 Pavement inspection

This section aims to provide a background about the pavement inspection function in the PMS. In addition, it aims to discuss the sampling procedures and the sample size effect on the Confidence Interval (CI).

It is impossible for highway agencies, due to limited cost and time, to monitor and assess the maintenance contractor based on the whole intended highway falling under the PBRMC. Each highway agency should define, in the contract, a sample unit of the road for evaluation in order to assess the maintenance contractors' performance within the contract period. To guarantee a representative sample from the overall road, De la Garza et al. (2008) introduced a sampling procedure for PBRMC evaluation. In this research, they presented a three-stage and seven-step statistical sampling procedure to ensure that the field inspection finding will be reliable and representative with a high CI of the actual condition of asset items in the desired road. The paper firstly presented the three-stage sampling procedures, which are as follows (De la Garza et al., 2008):

1. Perform a detailed analysis of the PBRMC characteristics.
2. Study potential sampling techniques that can be used to improve both the efficiency and effectiveness of the sample selection process.
3. Define a comprehensive methodology for the sample units' selection to ensure a high CI and guarantee that the findings from the inspected sample are representing the entire population.

After that, the paper presented different sampling techniques and proposed the sampling procedure in the form of seven-steps as shown in Figure 2-11:



Figure 2-11: Seven steps for pavement sampling procedures for PBRMC (De la Garza et al., 2008)

As shown in Figure 2-11, the first step is stratifying the population where; the population is divided into different areas depending on the information needed and the different parameters incorporated in the analysis (e.g. Rural vs. Urban areas). Then, the sample units should be defined where; each stratum is divided into sample units (e.g. sample unit length of 100 meter long). After that, the asset items on each sample unit should be defined via the Asset Density Database as shown in Table 2-4 (De la Garza et al., 2008).

Table 2-4: Asset density database (De la Garza et al., 2008)

Sample Unit (1)	Asset Items That Exist at Each Site (E = exists, NE = does not exist)				Total (N) (6)	Cum. (ΣN) (7)	Interval (8)
	Slopes (2)	Signals (3)	Guardrail (4)	Sidewalk (5)			
1	E	E	E	E	4	4	0-4
2	NE	E	NE	E	2	6	5-6
3	E	NE	E	NE	2	8	7-8
.
.
.
95	E	NE	E	E	3	ΣE_{95}	$\Sigma E_{94} + 1 - \Sigma E_{95}$
Total	ΣE 's	ΣE 's	ΣE 's	ΣE 's	ΣE 's		

E* (Existing), NE* (Not Existing)

Afterwards, a database with the asset items contained in each sample unit is created in order to guarantee the success of the random selection process. The following step is defining the parameters values that will be used in the sample size formulas (e.g. population size (N), Standard normal deviate ($Z_{\alpha/2}$), population proportion (p), and precision rate (e)). The sixth step is computing the required sample size for each asset item based on the parameters' values acquired from the previous step. Finally, the seventh step is performing the random selection of the sample units, as shown in Table 2-5.

Table 2-5: Random selection process of sample units (De la Garza et al., 2008)

Route (1)	Order of Selection ^a (2)	Unit Selected (3)	Database Used (4)	Statistics of Asset Inspected							
				Slopes (5)		Signals (6)		Guardrail (7)		Sidewalks (8)	
				n_R^b	n_A^c	n_R^b	n_A^c	n_R^b	n_A^c	n_R^b	n_A^c
A	1	3	1,2,3,4	70	1	22	0	66	1	14	0

	35	67	1,2,3,4	70	35	22	22	66	35	14	9

	50	5	1,3,4	70	48	22	22	66	50	14	14

	71	23	1,3	70	67	22	22	66	66	14	14

	74	10	1	70	70	22	22	66	66	14	14

NOTE: represents the asset items that met sufficiency.

^aRepresents the cumulative number of sites selected for inspection.

^bRepresents the minimum number of sites required for inspection in order to meet sufficiency.

^cRepresents the actual number of asset items selected for inspection.

As shown in Table 2-5, for the first 35 samples, all the asset items will be inspected. However, after 35 samples have been selected, the signals asset item was sufficiently met where; the number inspected is equal to the minimum number required for inspection. As a result, the slopes, guardrails, and sidewalks will be the asset items that need inspection. Following the same trend, for the next 15 samples, the sidewalks have been met. Then, the slopes and guardrails are the remaining asset items that need inspection. The trend continues until all are asset items are successfully inspected (De la Garza et al., 2008).

In addition, Mohamed et al. (1996) presented a study that shows the results of quantifying the effect of the sample unit size on the Pavement Condition Index (PCI)

values. In addition, it investigates the effect of reducing the number of the measured distresses on the PCI values. The results of this study were promising where; it indicated that the sample unit size might be reduced to approximately 40% of the standard PCI sample unit size within a five PCI points. However, it shall be hinted that the effect of the sample unit size on the PCI is a function of the PCI value of the pavement. Finally, they conducted a comparison between using the standard PCI procedures (using deduction curves) and the modified distress identification process (using Micro Paver) design. The comparison identified seven distresses types that are most useful to determine the M&R from both a project-level and a network-level PMS (Mohamed et al., 1996).

Finally, Shahin (2009) defined a project-level and network-level inspection plan to determine the number of samples to be inspected and the exact samples that should be randomly selected in order to guarantee a high consistency in the readings, resulting in a high CI. For the project-level PMS, he defined the number of inspection samples as a function of the total number of samples, the allowable error percentage, and the PCI standard deviation between the sample units in the section. Figure 2-12 shows the curves that were used to determine the total number of samples that needs to be surveyed to guarantee a 95% CI (5% allowable error) (Shahin, 2009).

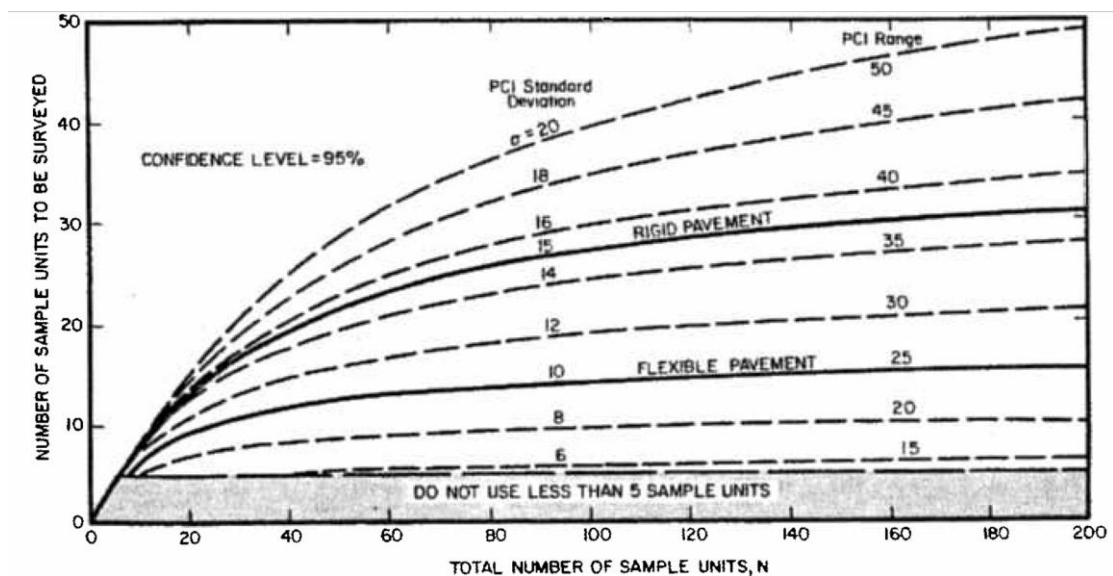


Figure 2-12: Selection of the Minimum Number of Sample Units (Shahin, 2009)

In addition, he recommended that the first inspection sample unit should be randomly chosen and the inspection sample units coming after that should be equally spaced throughout the section. This technique is called the “Systematic Random”. Figure 2-13 shows the calculation procedure of the systematic random technique for calculating the samples units that should be chosen for inspection (Shahin, 2009). Furthermore, he introduced a criterion that could be used by the highway agencies to determine the number of inspection sample units for a network-level PMS.

$$\begin{aligned}
 \text{Total Number of Sample Units In Section (N)} &= 47 \\
 \text{Minimum Number of Units to be Surveyed (n)} &= 13 \\
 \text{Interval (i)} &= \frac{N}{n} = \frac{47}{13} = 3.6 = 3 \\
 \text{Random Start (S)} &= 3
 \end{aligned}$$

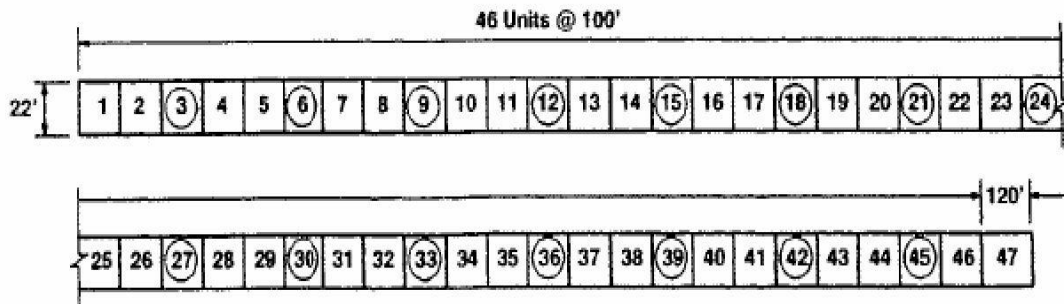


Figure 2-13: Systematic Random Sampling (Shahin, 2009)

2.3.5 Pavement condition rating

This section aims to provide a background about the condition rating and its role in the PMS. Moreover, it aims to discuss different condition rating systems and examples that were developed by different institutes within different countries. Pavement condition rating is the translation module from a linguistic inspection results into a numerical PCI. An improper pavement condition rating will directly lead to erroneous PCI results not representing the actual pavement condition. The main purpose of the pavement condition rating is to calculate the PCI with an objective of evaluating the maintenance contractor performance within the contract period.

A tremendous number of institutes from different countries developed pavement condition rating systems. For instance, NYSDOT (2010) has developed a report that describes the procedures of how to assess and quantify the pavement condition. They calculated the PCI based on the deduction curves, as shown in Figure 2-14, for each aspect directly affecting the PCI value. In addition, they identified four general aspects for measuring the pavement condition, which are as follows (NSYDOT, 2010):

1. Surface distress
2. Ride quality (IRI)
3. Structural capacity
4. Friction

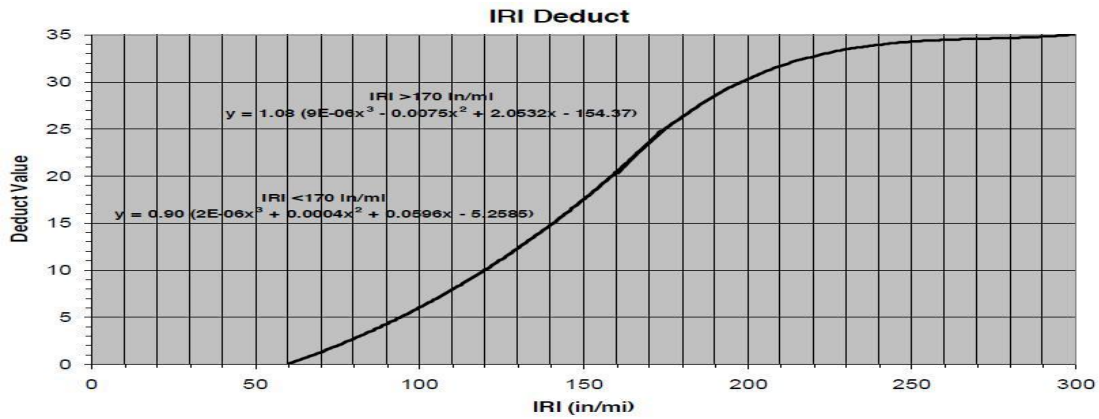


Figure 2-14: PCI Deduction curve for IRI (NSYDOT, 2010)

In addition, PMS (2012) developed a manual that discusses, in details, the different distresses and introduces a condition rating system for calculating the PCI. Moreover, the manual recommended the best M&R strategies to be implemented based on both a linguistic and numerical condition rating system (PMS, 2012). Moreover, Highway Preservation Systems (2010) has developed a detailed study about the direct calculation of the PCI from the distresses. In this study, they firstly defined the distresses, the severity and extent levels for each distress solely. After that, they assigned a weight for each distress, based on how it affects the PCI value, to result in a deduction value for each distress. Finally, the summation of the deduction values will be subtracted from the past PCI to get the current PCI (Highway Preservation System, 2010).

Moving towards the end, Opus International Consultants (Canada) Limited (2012) prepared a surface condition rating manual. In this manual, they discussed the different distresses types and their units of measurement. Then, they defined the severity and extent levels for each distress. After that, they introduced a pavement inspection form to evaluate the pavement performance and calculate the PCI based on (Opus International Consultants Limited, 2012).

2.3.6 Future deterioration prediction

2.3.6.1 Introduction

Pavement deterioration is “a mathematical description of the expected values that pavements’ attribute will take during a specified analysis period” (Hudson et al. 1979). An attribute is a property from the pavement segment that provides an expressive measure of the behavior, performance, adequacy, cost, and value of the pavement. It can be defined as “a mathematical description that can be used to predict the future pavement deterioration based on the present pavement condition, deterioration factors, and the effect of maintenance” (OECD, 1987). Deterioration models usually express the future condition state of the pavement, in terms of explicatory variables, that include the pavement structure, age, traffic loads, and environmental variables.

Deterioration models are able to predict either single or combined pavement condition indicators. However, this study suggests that a single deterioration model for the pre-defined contractual KPIs’ is vital for highway agencies to assist them in better estimation for the overall pavement condition resulting in a better improvement in the precision of planning for the applied M&R strategies. Thus, this will lead to an astronomical extension in the pavement service life and LOS. Researchers have realized that the successful PMS mostly depend on its deterioration model. In addition, the superior deterioration models lead to a considerable savings, which is the outcome of the highway agencies (Hudson et al., 1997, Mohesni et al., 1992, Vepaet al., 1996).

Deterioration models are the key for the decision-making support as they are useful to answer the following questions:

1. What to do for this entire highway to guarantee meeting the acceptable road physical condition?
2. Where to do it (the segments that need M&R)?

3. How to do it (the M&R strategy that needs to be implemented in each segment to ensure meeting the KPIs)?
4. When to do it (the optimum time to apply M&R for each segment to minimize the LCC)?

2.3.6.2 Deterioration model development methods

Deterioration models have been categorized into the following, based on the development method, (FHWA, 1990):

1. Empirical Method
2. Mechanistic Method
3. Mechanistic - Empirical Method
4. Probabilistic Method
5. Bayesian Method

2.3.6.2.1 Empirical Method

The empirical method depends mainly on collection of a huge amount of data without thinking of their significance or the expected outcome. It is derived from the basis of statistical models. It is useful for conducting statistical analysis, statistical modeling, and statistical accuracy testing (Mubaraki, 2010).

2.3.6.2.2 Mechanistic Method

The Mechanistic method is based on the theory of mechanics. It includes the elastic and finite element methods. However, it depends on detailed structural information, which limits the calculations to segments for which the detailed data is available. Thus, this method is not appropriate for predicting the condition as they are only dependent on the surface data (Mubaraki, 2010).

2.3.6.2.3 Mechanistic – Empirical Method

It is sometimes referred to as the analytical – empirical method. It has been widely applied on the design of flexible pavements. It consists mainly of two roles (Mubaraki, 2010):

1. Calculation of the pavement materials with response to the applied loading (Traffic).
2. Pavement performance prediction from these responses.

This method is a promising method in the pavement management, which depends on the pavement material data. Thus, this study could not be carried out using this method.

2.3.6.2.4 Probabilistic Method

This method mainly treats the pavement condition as a random variable with probabilities accompanied with their values, described by probability distribution. Thus, a transition probability matrix is introduced to identify the pavement future condition state based on its initial state. This transition probability matrix should be developed based on the combination of factors that affect the pavement condition. The probabilistic method is applicable when there is a lack of available data to be used.

2.3.6.2.5 Bayesian Method

Bayesian methods are dependent on the combination of the observed data and expert experience using Bayesian regression techniques, initially introduced by Thomas (1993). In Bayesian regression analysis, the regression parameters are considered as random variables with probability distribution. Bayesian theorem can be mathematically expressed as shown in Equation 2-1 (Thomas, 1993):

Equation 2-1: Bayesian Theorem Equation

$$P(p|x) = \frac{P(x|p) \cdot x \cdot P(p)}{\sum [P(x|p) \cdot x \cdot P(p)]}$$

Where;

- $P(x)$ is the distribution of variants over all possible fraction variants
- $P(p)$ is the prior distribution
- $P(x|p)$ is the sampling distribution
- $P(p|x)$ is the posterior distribution

2.3.6.3 Prediction model types

Performance modeling is used to predict the performance and deterioration of the pavement, as a function of time, in order to be able to predict the pavement service life. Figure 2-15 shows the deterioration modeling and the direct impact of the M&R strategies on the pavement condition (FHWA, 2002b).

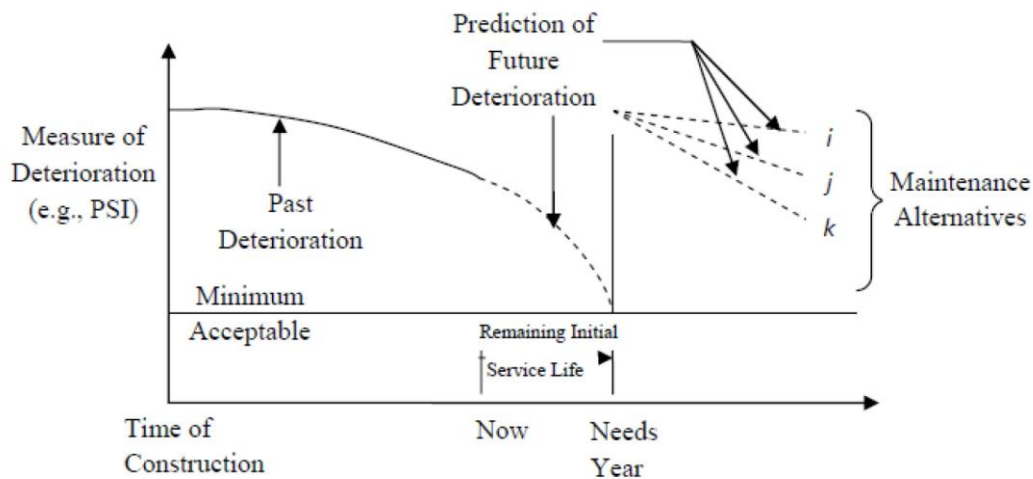


Figure 2-15: Deterioration modeling and impact of M&R strategies on the pavement condition (FHWA, 2002b)

Different researchers have classified the prediction models for the PMS from different perspectives. Nevertheless, there are three major classification models for prediction in PMS:

1. Deterministic models
2. Probabilistic models
3. Bayesian models

However, Mahoney (1990) classified the prediction models, based on an earlier work of Lytton (1987), into two types or classes of models. He considered the project-level and network-level PMS levels under the two basic classes of models, which are the following (Mahoney, 1990 and Lytton, 1987):

1. Deterministic models: It is calculated as a numerical value, based on a mathematical function of observed condition (Robinson et al., 1996). The future condition of the pavement is predicted at a certain time period, based on the past pavement information (Durango, 2002).
2. Probabilistic models: It predicts the pavement performance through assigning a probability under which the pavement would fall into a particular condition state (Durango & Madanat, 2002).

George et al. (1996) classified the prediction model into two types namely; disaggregate and aggregate models. The disaggregate model mainly predicts the future performance of an individual measure of a certain distress. On the contrary, the aggregate models predict the composite measures such as PCI (George et al., 1996).

Hass et al. (1994) developed another classification where; they classified the prediction models into four fundamental types:

1. Mechanistic models: They are based on some response parameters due to traffic and/or environmental actions.
2. Empirical (Regression) models: The dependent deterioration variable, such as the PCI, is directly linked to one or more independent variables such as; axle load reputations, pavement layer thickness and properties, environmental factors and their interactions, and traffic.
3. Mechanistic-Empirical models: Regression equation relates the response parameter to the structural deterioration (distress types and/or IRI).

4. Subjective (Probabilistic) models: The experience is the base for formulating a structured transition probability matrix to develop the prediction model.

The main choice of the type of model to follow is the available data. It has a great influence on which method of modeling and which types of model the study will be carried out. In this study, the deterministic and probabilistic models will be discussed as the study compared the results of the PCI using both a Markov-based and a regression-based deterioration prediction models.

2.3.6.3.1 Deterministic models

Regression, empirical, and combined mechanistic-empirical methods can be used to develop a deterministic model. During the mathematical formula selection, these two items should be considered where; the pavement performance model should fit the observed data and the regression-statistical data as well (Li Z. , 1997).

Numerous numbers of researches were conducted on the future deterioration prediction using the regression modeling approach. El-Assaly et al. (2002) developed a deterioration model for the highway network in Alberta, Canada. The objective of this study was to predict the performance change rate, the future deterioration rate, and the years to reach a specific limit. This study was conducted only on the IRI as a main KPI to track the pavement LOS (El-Assaly et al., 2002). In addition, Ferreira et al. (2010) developed a pavement performance models to be used in the Portuguese PMS. This study was showing different performance models that were developed through different institutions and compared the results, obtained from the bases studies, to choose the best model to be applied on the Portuguese highway network (Ferreira et al., 2010).

Finally, George (2000) developed a full PMS including prediction models and feedback systems. This study introduced a prediction model for Mississippi Department of Transportation (MDOT) that performs the following:

1. M&R planning
2. Budgeting

3. LCC analysis
4. Multi-year optimization of M&R programs
5. Authentication of design alternatives

The prediction models were based on regression-analysis as the primary tool for developing the models. In this study, the prediction model was applied on five different pavement types namely; flexible pavements, overlaid flexible pavements, composite pavements, jointed concrete pavements, and continuously reinforced concrete pavements. The study concluded that employing the Bayesian regression, resulted in a better prediction models. Finally, a feedback program was developed in order to compute the load index of the original pavements of all types. The main target of the developed feedback system was to compare the actual condition with the predicted condition and improve the prediction model efficiency (George, 2000).

2.3.6.3.2 Probabilistic models

Probabilistic models are developed to characterize the uncertain behavior of pavement deterioration processes (Li Z., 2005 and Panthi, 2009). The Markov model, as a type of probabilistic models, has showed to be an effective performance-modeling tool among various researchers (Butt et al., 1987, Haas et al., 1994, Li Z., 1997 and Madanat et al., 1995). Markov-based modeling is commonly used due to its ability to capture the probabilistic behavior of pavement, through the transition probability matrix, and the time dependent uncertainty deterioration process, taking into consideration different M&R strategies (Panthi, 2009). It was mainly built on the pavement transformation from a certain condition state to another one over a certain time-slot. Li (1997) classified the Markov models into homogeneous and non-homogeneous models. He indicated that the homogeneous Markov models assume that the variables (such as traffic loads, environmental condition, etc.) are constant throughout the analysis period. However, the non-homogeneous Markov models accounts for a certain change rate at each different stage. In addition, he added that Markov-chain models are developed either using time-based analysis, through estimating the probability of time needed to transform from one condition state to another, or condition state-based analysis, through estimating the probability of

transforming from one condition state to another within a pre-defined analysis period (Li Z. , 1997).

Markov-Chain models have been successfully employed by many researchers in the field of PMS (Abaza & Ashur, 1999 and Li et al., 1996). In addition, Adedimila, et al. (2009) presented the pavement deterioration model, as a part of their PMS. They developed the deterioration model, based on historical records of pavement performance, to get the transition probability matrix and run for an optimum M&R action plan through the pavement service life. In addition, they carried-out BCA to compare their results with the traditional results. It was obvious that the impressive results showed an enormous difference from 57.2 BCA to 466.9 BCA. (Adedimila et al., 2009)

Haider et al. (2012) developed a Markov-chain model to evaluate the effectiveness of M&R strategies at a network-level PMS. They concluded that the advantages of using Markov-chain model included the following:

1. The ability to model both the pavement deterioration and M&R action plan at the same time.
2. The ability to evaluate the impact of initial PCI on both the short-term and long-term performance.
3. The ability to compare the outcome of different M&R action plans.

Furthermore, Tjan and Pitaloka (2005) developed a future prediction model using Markov probability transition matrix. They constructed a ten-points range for the pavement condition to develop a ten by ten pavement condition matrix (10 x 10). The results showed a deviation of 5.5% up to 10.6% of the total length of the pavements, which is still within the acceptable level for a network-level PMS (Tjan & Pitaloka, 2005). Surendrakumar et al. (2013) developed a Decision-Support System (DSS) to predict the future condition of the pavement. The model was based on a Markovian probability process and calculating the successive transition matrices for predicting the condition state of the pavements. The results showed the capability of the Markovian probability process tool to predict and calculate the future pavement condition state at any time. In addition, the enhancement in the pavement condition

can be easily calculated to track the effect of any M&R strategy. Finally, it will aid in finding the optimum M&R action plan with respect to the budget and condition constraints (Surendrakumar et al., 2013).

Moreover, Ortiz-Garcia et al. (2006) discussed the derivation of the Markovian transition probability matrices for the pavement future deterioration modeling. They used two approaches to develop the transition matrix. The first one assumes the availability of the historical network condition data to base the transition probability matrix on. While, the second approach utilizes a regression curve from the original data to develop the initial Markovian probability transition matrix based on. It was obvious that the results of the second approach were much closer to the original results. Finally, Mbwana (2001) introduced a framework for developing a Markovian multi-objective PMS. The objective of this research was to allow decision-makers to have an effective tool that selects the M&R action plan for a network-level PMS (Mbwana, 2001).

2.3.6.3.3 Artificial Intelligence (AI) models

Several researches have applied Artificial Neural Networks (ANN) to develop future pavement deterioration models. For example, MDOT developed several ANN models to predict the pavement condition for five different types of pavements such as; flexible pavements, overlaid flexible pavements, composite pavements , jointed pavements, and continuously reinforced concrete pavements (Shekharan, 2000).

In addition, Gryp et al. (1998) determined the Visual Condition Index (VCI) of flexible pavements using ANN. Yang et al. (2003) conducted another example where; they applied ANN to forecast both the pavement crack index and the pavement condition rating.

Suman and Sinha (2012) have developed a pavement condition-forecasting model through ANN. The main objective of this study was to give a considerable contribution for supporting the management decision, in the area of pavement performance prediction (Suman and Sinha, 2012). Furthermore, Yang (2004) developed a road crack condition performance model using both Markov-chain model

and ANN. The results of this study showed that Markov-chain models provided a more applicable methodology for modeling the pavement deterioration process concerning cracks.

2.3.7 Pavement M&R strategies

This section aims to provide a background about the different M&R strategies used for improving both the PCI and the LOS. Moreover, it aims to discuss different case studies about the application of M&R action plans to maximize the PCI. The main purpose is to introduce the different M&R strategies and be able to predict its effect on the future deterioration curve (through the PCI after application) in order to aid the decision-making support software to reach the best M&R action plan that minimizes the LCC from both the project-level and network-level perspectives.

Highway agencies have expanded in the construction of pavement networks that are vital to the economic prosperity and vitality of the nation. There are numerous M&R manuals and standards that were developed by different institutes in different countries to standardize the M&R strategies use and effect on the pavement condition (Nebraska Department of Roads, 2002 and Bureau of Design and Environment, 2010). However, these networks are currently facing a rapid deterioration rate, as most of the highway agencies cannot afford to reconstruct the highways in a timely manner. As a result, Thomas et al. (2009) introduced a guide for the best management practices for Hot-mix Asphalt (HMA) M&R strategies. Consequently, highway agencies have applied low-cost preventive maintenance (PM) techniques such as crack and surface treatments to slow down the deterioration rates of the pavements. In addition, by applying the PM techniques, the pavement service life will be extended and thus, will delay the re-construction time. Figure 2-16 shows the results of the analysis indicating a service life extension of approximately 3 – 5 years (Thomas et al., 2009).

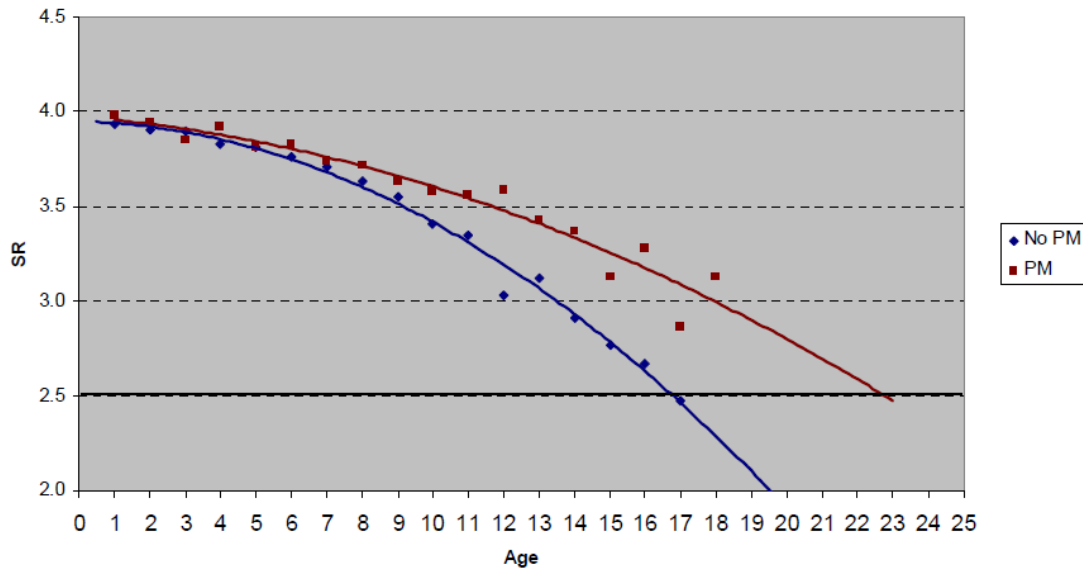


Figure 2-16: Effect of PM on the Pavement Service Life (Age) (Thomas et al., 2009)

Furthermore, Li et al. (2001) developed an integrated dynamic performance prediction model with the M&R action plan. In this study, they defined each M&R strategy in terms of structural design, construction criteria, paving materials, M&R strategy effect on the existing pavement structural and functional performance, and M&R strategy unit cost. They also defined the distresses weights to analyze the effect of each distress on the PCI. Moreover, they identified the effect of each M&R strategy on both the pavement service life and the PCI. Finally, the model was successfully applied on a small road network and the results were promising where; they were able to achieve the most cost-effective M&R action plan within the 7-years analysis period (Li et al., 2001).

The Tennessee Department of Transportation conducted another research in 2009. In this study, they were applying pavement PM program, which can improve the PCI and slow down the future deterioration. In addition, they emphasized on the methodology for determining the optimal PM application time to reduce the future deterioration rate for the highway from one side and to achieve the most cost-effective M&R action plan from the other side. Finally, they recommended that the PM should be chosen based on three factors as follows (Baoshan & Qiao, 2009 and Dong, 2011):

1. Traffic volume
2. Distress type
3. Distress severity level

In addition, Hicks et al. (2000) prepared a report that introduced the selection criteria for the best applicable PM strategy on the flexible pavements. This report specifically addresses PM where; it includes the available PM strategies, the time and location where they should be used, the PM cost effectiveness, the factors that should be taken into consideration while selecting the appropriate PM strategy, and the methodology on how to determine the most effective PM treatment. In this report, they illustrated on the essence of applying PM strategies to improve the pavement condition and achieve an effective LCC within the pavement service life. Figure 2-17 shows the effect of applying PM on the pavement condition. It was apparent that an extension of the service life is guaranteed, in case of applying PM, compared to the other case of not applying PM. In addition, it is obvious that the Net Present Value (NPV) is much lesser for scenario (A) of applying PM compared to scenario (B) of not applying PM (Hicks et al., 2000).

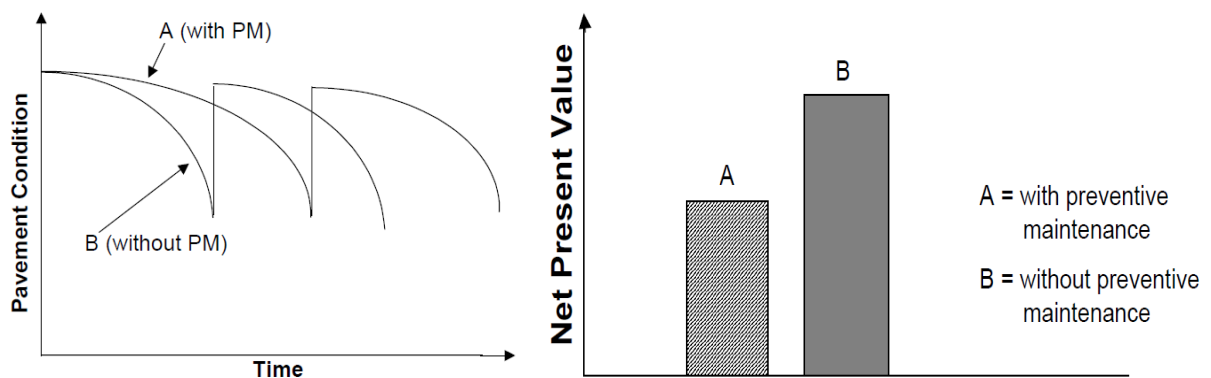


Figure 2-17: PM effect on PCI and comparison of the NPV of pavement with PM and without PM (Hicks et al., 2000)

In addition, the selection criterion was based on the concept of “Decision Tree”. As the terminology implies, “decision trees incorporate a set of criteria for identifying a particular PM strategy through the use of “branches.” Each branch represents a specific set of conditions (in terms of factors such as pavement type, distress type and level, traffic volume, and functional classification) that ultimately leads to the identification of a particular treatment” (Hicks et al., 2000). Finally, Figure 2-18 shows a typical pavement deterioration curve and the difference between applying PM and not applying PM. It is noticeable that the unit cost per square meter, in the case of applying PM, is much more less than that of not applying PM. In addition, the LOS of the pavement is better in case of PM giving the highway agencies the opportunity to own longer service life highways (Hicks et al., 2000).

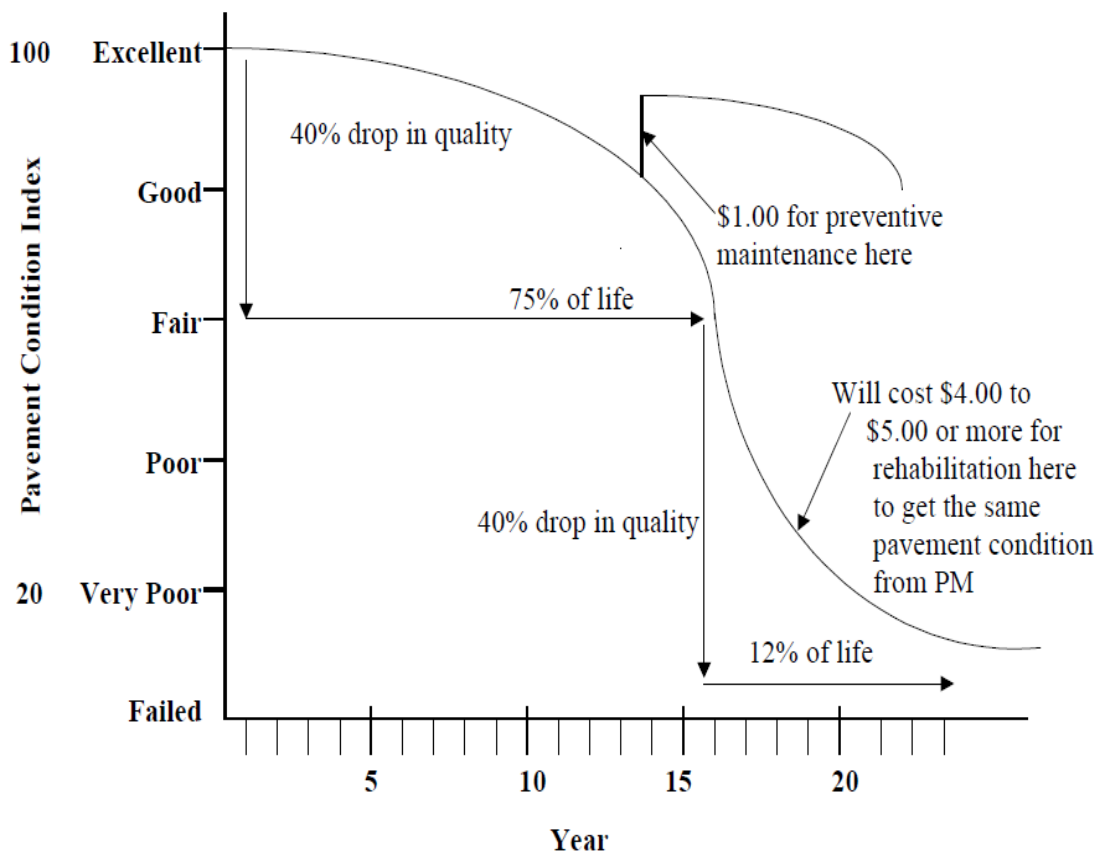


Figure 2-18: Cost Comparison between applying PM and not applying PM (Hicks et al., 2000)

2.3.8 Applications on PMS

This section aims to present several case studies about the application of PMS in different countries. The main purpose of this section is to pinpoint on the essence of a proper PMS to support the decision-makers in their critical decision. In addition, it was obvious, as mentioned above, that the cost savings increase whenever a proper M&R action plan is successfully reached.

Farashah (2012) developed an application for municipal PMS on the city of Markham. The results of this study were auspicious, concluding that Markov deterioration models are effective to predict the pavement performance. In addition, it showed that optimization is necessary to prioritize the highways' M&R action plans at a network-level PMS (Farashah, 2012). Another study was conducted by Tsai et al. (2010) where; it targeted the development of a project-level PMS that is able to develop a predication model for each distress and identify the most influencing distress on the PCI.

Javed (2011) has developed an integrated prioritization and optimization approach for pavement management. In this study, a two-stage approach to overcome the budget allocation problem of highway asset management was developed in order to incorporate the user priority preferences into the PMS programming process (Javed, 2011). Finally, Mubaraki (2010) developed a prediction deterioration model for Saudi Arabia urban road network. This study enhanced a network-level PMS that investigates the behavior of different distress types. In addition, two pavement condition models were developed for predicting the PCI of the main urban pavements and the secondary urban pavements respectively. Finally, the procedures of implementing these models on different cases have been introduced to generalize the developed model (Mubaraki, 2010).

2.3.9 PMS conclusions

This section aims to sum up the literature review about PMS and clarify the missing gaps in the literature in order to formulate the research objectives

The term PMS has initially started at the late 1960s' and early 1970s' where; it was defined as "the means of describing the range of activities that are involved in providing serviceable pavements." At this time, it was based on systems engineering approach to the problems of economical design, construction and pavement M&R (Peterson, 1987). The first sector of this section aimed to provide a historical background about the PMS and different applied successful systems in different countries. Then, the second sector was divided into five main disciplines namely; pavement inventory, pavement inspection, pavement condition rating system, pavement future deterioration prediction, and pavement M&R strategies. Each discipline has been vertically and uniquely developing, as discussed above in this sector, and different integrated system has been presented regarding the fully developed PMS conducted by different researchers and institutes. Several researchers concluded that the backbone for a successful PMS is the precision and accuracy of its' future deterioration prediction model. It was apparent that it acts as a base line that aids the decision-making support tool to take critical decisions and obtain the best M&R action plan. It was obvious that the majority of existing commercial PMS are not geared towards optimizing the pavement performance vs. the P/I costs of PBRMC. As a result, the author recognized the essence of integrating the decision-making backbone (future deterioration prediction model), acting on the be-half of the PMS, with the KPIs' and P/I system, acting on the be-half of the PBRMC, to study the effect of changing the KPIs' limit and P/I system on the financial status of the contract. Finally, the third section showed different PMS applications by several institutions in different countries. It was apparent that successful PMS would result in an enhanced efficiency of expenditures spending and better pavement and/or network condition in developed and developing countries directing the countries towards an enhanced infrastructure condition.

2.4 Optimization

This section will discuss the optimization application in PMS. By the virtue of its complex nature, infrastructure asset management comprises a wide spectrum of interrelated variables. This multifaceted character of the infrastructure asset management initiated the need for engineering modeling and decision-making support tools and techniques to be on the top of the necessities.

2.4.1 Introduction

Optimization, as a decision-making support tool, is a key for any infrastructure asset management. Alyami (2012) defined it as “a branch of mathematics concerned with finding the optimum alternative to complex problems in accordance with established objectives and constraints” (Alyami, 2012). Asset managers have always the main objective of seeking a minimal LCC and a maximum LOS for the asset. In order to reach this valid objective, there is an urgent need for a tool that automatically evaluates the different valid and/or invalid solutions and tackles their effect on the LCC and LOS. In addition, there are millions of both valid and/or invalid solutions, which make it impossible for a simple tool to try over various solutions to reach the near optimum one. As a result, the optimization was introduced to this research as a decision-making support tool, that supports both the asset managers and the maintenance contractors, to reach their goal (objective) as per defined throughout the numerically developed model.

2.4.2 Optimization algorithms

2.4.2.1 Introduction

There are numerous optimization techniques available, such as linear programming, non-linear programming, integer programming, etc. (Wintson, 1995 and Rardin, 2000). Linear and integer programming are the two most commonly used optimization techniques for both project-level and network-level PMS. The following summarizes both techniques and the algorithms used for implementing each technique (Gao, 2004).

2.4.2.2 Integer Programming

An integer-programming model is “an optimization model in which all decision variables can only have the values of integers” (Gao, 2004). From a project-level perspective, each maintenance strategy is assigned a certain integer from 0 (Do Nothing) to 9 (Replacement) with increments of 1. The decision variable is x_{it} where; i refers to rehabilitation treatment methods, and t refers to the future year.

The main objective of applying the project-level PMS under the integer programming is to determine the value of the x_{it} for each year in each project to achieve a near optimum solution. The integer programming is sometimes called “combinatorial optimization”, because the model is concerned with finding answers to questions such as “Does a particular arrangement exist?” or “How many arrangements of some set of discrete objects exist to satisfy certain constraints?” (Gao, 2004).

The asset managers, involved in the decision-making process, easily understand the integer-programming concept. The key decisions variables, facing most highway agencies, are the M&R action applied time and strategy. However, the difficulty comes from the number of combinations that goes under the feasible region.

Fwa et al. (1994) highlighted on the two major issues that dramatically increase the difficulties of solving a typical integer-programming model. The first one is the integer nature of the decision variables that restrict the methods (algorithms)

that can deal with integer variables. The second one is called “Combinatorial Explosion” of the possible solution. For instance, if we are a network-level PMS having 500 projects, and each project have 10 M&R strategies alternatives (such as Do Nothing, Crack Sealing, Slurry Sealing, Micro-surfacing, Thin Overlay, Structural Overlay, Patching, Milling and filling, Deep patching, and Reconstruction); then, for an analysis period of 5 years, there will be $(25,000)^5 = 9.76 * 10^{21}$ possible solutions. This will take decades to reach the best solution.

Because of these complexities, heuristic methods are mostly used to solve such models. They are “approximations of true optimization techniques”. The solutions obtained by heuristic methods are all feasible solutions derived from certain searching methods that are not guaranteed to yield an exact optimum (Rardin, 2000).

One of the simplest heuristic methods is the “Improving-search Heuristics Method”. This method begins with an initial feasible solution, then starts to iterate. Each iteration considers neighbors of the current solution and tries to advance to a feasible one, resulting in a better objective value. Through this process, a local optimum and heuristic solution is found. Although the improving-search algorithm of this method can be quite effective, but the solution obtained is very likely to be local optima instead of true optima. To reduce the chance of reaching a local optimal solution that may significantly deviate from that of the true optima for a specific problem, many other methods have been explored to produce more robust algorithms for obtaining local optima, which is closer to its true optima. (Gao, 2004)

GAs’ is one of such methods used by many researchers in both project-level and network-level PMS to solve an integer-programming model (Chan et al., 1994, Ferreira et al., 2001 and Fwa et al., 1996). GAs’ was firstly introduced in Holland at 1975 (Holland, 1975). The method firstly begins with two feasible solutions. During each iteration, a new solution is created by combining pairs of previous solutions. As a result, this method attempts to parallel the process of natural selection to find better solutions. There are many variations of GA methods. The differences are primarily based on either how to select the current solutions pairs or how to produce new ones via combinations. The idea is concerned with how to decide which new and/or old

solutions will survive in the next population and how to maintain diversity in the population as the search advances from generation to generation. Although the method is very promising, the solution obtained is still a heuristic solution, and it loses the advantage of finding a true optimum solution with increasing the problem complexity (Gao, 2004).

Additionally, there are many other heuristic methods other than that discussed above (Rardin, 2000). However, they are also based on using the integer programming approach to reach a true optimum solution of a mega-scale complex problem that could not be computationally solved. Therefore, this initiates the need for a heuristic solution with no guarantee to reach a true optimal solution.

2.4.2.3 Linear Programming

A linear program is “an optimization model in which the objective function and all constraint functions are linear in the decision variables.” In a linear program for a network-level PMS, Markov Chains are mostly used for the deterioration modeling to forecast future KPIs’ (Gao, 2004).

In project-level PMS, the M&R strategy is selected annually to cover the pre-defined analysis period, and then the effect on the pavement KPIs’ and expenditures is studied. In the optimization approach, different M&R strategies combinatory alternatives are considered where; the alternative that has a minimal LCC and meets the contractually defined KPIs’ will be selected as the optimum solution.

In spite of the advantage of reaching the optimum solution, some drawback were discovered other than the struggles of solving the optimization problem. Some highway agencies reported that, “Upper management had difficulty in comprehending and, therefore were suspicious of the results of the rehabilitation plans generated by the optimization methods.” Additionally, this makes it more complex to support both the financial and technical outcomes of such M&R action plans (Zimmerman et al., 2000). Moreover, Due to the complexity of the generated optimization results from this method, some highway agencies were hesitant to use this method for the fear of losing control on their programming and scheduling processes (FHWA, 1997).

2.4.3 Applications of Optimization on PMS

Various approaches for PMS optimization of M&R strategies programming have been proposed in recent years. Common components of these approaches are as follows (Akyildiz, 2004):

1. Identification of network information system
2. Evaluation of current needs
3. Definition of treatment strategies
4. Prediction of future condition for development of assets' optimization algorithm
5. Selection of appropriate treatments

The two key elements in the different optimization approaches are the optimization algorithm and the future deterioration modeling. Those elements mainly vary according to the researchers' approach to solve the problem. Mbwana and Turnquist (1996) introduced a network-level PMS using a mega-scale linear programming algorithm, converted from dynamic programming formulation, with an objective of minimizing the overall network LCC (Mbwana & Turnquist, 1996). However, Wang et al. (2003) were not convinced with this approach due to its complexity and disputable assumptions.

Another approach used in modeling the network-level PMS is goal programming. Raviarala et al. (1997) preferred the goal programming because of its strength to embrace conflicting objective with different importance weights. Nevertheless, they stated that goal programming encounters some disadvantages with integrating the Markov Transition Probabilities into the optimization procedure. In addition, it was recognized that the integer programming, used in this approach, showed to be unsuitable to mega-scale networks, because of the high computational requirements. Consequently, Raviarala et al. (1997) proposed a linear program to attain the optimal multi-year maintenance network program. However, the network condition assessment involved different tasks, beginning with defining the pavement states, and ending up with creating an asset inventory and inspection data, which controls the specifications of the three key processes, which are as follows:

1. Treatment identification
2. Condition-treatment matching
3. Estimation of pavement condition-state transition times

Li et al. (1997) declared that choosing the optimization algorithm is as much important as choosing the performance prediction model. As a result, they emphasized on the necessity of creating a deterioration model that is able to consider the M&R effect on the deterioration rate after being applied. Additionally, Markov decision process does not take into account the direct effect of applying a treatment into a segment, assuming that the applied M&R does not have any effect on the deterioration rate of the pavement. This assumption totally contradicts what actually happens in the field. Therefore, they introduced a non-homogeneous (Time-related) markov decision process that assumes a new deterioration rate, based on Ontario Asphalt Deterioration Equation, for the segment where the M&R strategy was applied on. Moreover, they defined a standard unit cost for each M&R strategy and quantified the numerical effect of each M&R strategy on the pavement condition, expressed in terms of KPIs'. The developed model functions through an integer programming approach with an objective of maximizing the Benefits-Costs Ratio (BCR) by annually selecting the most cost effective M&R strategies. The model had certain pre-defined budget and performance constraints that should be met by the selected M&R strategies. The comparison of the different M&R alternatives was not only based on the unit cost of the M&R strategy, but it was also based on the quantitative effect of each M&R strategy on the future pavement LOS (Li et al., 1997).

Liu and Wang (1996) used linear programming approach to perform the optimization. They also developed a network-level optimization model that maximizes the network performance, within the available budget, over the planning time horizon. The outcome of their proposed model can be summarized as follows (Liu & Wang, 1996):

1. Budget allocation for different M&R actions
2. Pavement annual condition prediction

3. Proportions of the pavements expected to be in each condition state at the beginning of each year

Furthermore, Haroun (2005) has developed a comparison of three AI approaches; Multilayer Perceptron (MLP), GAs', Self-Organizing Map (SOM). The main aim for this comparison was improving the automated asphalt pavement crack classification using computer vision. The study resulted in a very high accuracy ranges as follows: 98.6% for MLP, 98.2% for GA, and 98.4% for SOM (Haroun, 2005). In addition, Piya et al. (2005) introduced a multi-layer pavement maintenance programming that considers the uncertainties in the deterioration model. They developed a simulation-based GAs' approach that could result in a multi-year M&R action plan for the pavement. They used a stochastic simulation to simulate the uncertainty of the future pavement condition, based on the calibrated deterioration model. The results of this study showed an underestimated M&R budget and overestimated network performance because of taking the uncertainties into consideration in the future pavement condition calculation.

Finally, Tack and Chou (2002) proved the effectiveness of GAs' in maximizing the pavement condition through determining the best-applied M&R strategies for the LCC analysis period. After that, an investigation for dynamic programming algorithm was conducted in conjunction with two different GAs' techniques, namely Simple GAs' (SGA) and Pre-constrained GAs' (PCGA), to generate near optimal solutions. They also indicated that the high degree of flexibility and scalability inherent in GAs' technique gives it a great opportunity, over the dynamic programming, to deal with different pavement deterioration models and M&R strategies. As a result, it was obvious that dynamic programming is inappropriate in dealing and adjusting with new decision variables introduced in the model. Therefore, they concluded that SGA and PCGA are easier to implement to PMS than the dynamic programming algorithm (Tack & Chou, 2002). In addition, Cheu et al. (2004) concludes this argument by ensuring that GAs' is suitable for problems with plentiful number of decision variables and constraints due to its flexibility in the objective functions coding.

2.4.4 Optimization conclusions

Optimization has been extensively used in PMS with different applications and through different algorithms. Many researches have conducted comparisons between different optimization algorithms that lead to the near optimal solution for a network-level PMS. Mostly, the GAs' results were promising giving a green key for GAs' to be applied in this study as the optimization algorithm for both the project-level and the network-level PMS. The project-level operates for a single-objective function, but the network-level PMS operates for a multiple-objective function. As a result, GAs' was chosen for application on this study because of its' strength in dealing with both single-objective and multi-objective functions. Finally, Cheu et al. (2004) ensured that GAs' are suitable for problems with plentiful number of decision variables and constraints due to its flexibility of the objective functions formulation.

2.5 Summary

In conclusion, the PBRMC research has focused more on the theoretical and contractual issues, looking from the highway agencies' perspective, while less research was focused on the maintenance contractor and how the maintenance contractor should optimize his resources to benefit from this type of contract. Moreover, researchers focused on defining the KPIs' that will guarantee a good highway/network condition for the highway agencies. As a result, based on the previous research, P/I system has to be reasonable enough to both guarantee a proper condition for the highways and enable the maintenance contractor to have more flexibility in achieving the KPIs'.

For PMS, several researchers have performed various PMS to reach the optimum LCC. However, the objective of this study was not only reaching the optimum LCC, but it was also targeting a full study of the PBRMC from a third view where; the P/I system will be applied on the financial module of the future deterioration model. In addition, it will help the highway agency, as being the owner, to choose an appropriate sampling percentage to guarantee a proper CI of the maintenance contractors' performance. Finally, it will act a decision-making support tool, for the maintenance contractors, to prevent entering to the dilemma of paying penalties due to not meeting the pre-defined KPIs'.

Finally, GAS' has shown to be one of the best-suggested algorithms to be used in the PMS. In this study, GAS' was chosen to be the optimization algorithm for both the project-level and the network-level PMS. Moving towards the end, an integrated GIS is developed to give the asset managers the full opportunity to track the maintenance contractors' performance through. In addition, it acts as a "Visualization tool" that gives the highway agencies the privilege to track the highway performance under the PBRMC.

3 CHAPTER 3 – RESEARCH METHODOLOGY

In order to reach the research objectives, which were stated in chapter one, a research methodology should be clearly stated and specified. As a result, this chapter highlights the proposed methodology for achieving the objectives of this research.

3.1 Introduction

In this chapter, the research methodology is introduced and discussed in details. The chapter begins with stating the research scope and objectives. Subsequently, the research methodology is proposed to detail the approach followed to achieve the research objectives. This chapter will discuss the following main topics:

1. Research Scope and Objectives
2. Research Methodology
3. Need for P/I System for KPIs'
4. Need for Optimization
5. Need for Visualization

Accordingly, each section is discussed in depth with a main target of achieving the research objectives.

3.2 Research Scope and Objectives

This research aims to build a fully IHAMS, which is able to consider the unique contractual requirements of PBRMC. In order to serve the needs of road operators, the system needs to consider both project-level and network level asset management decisions. The system needs to have spatial visualization capabilities due to the networked nature and large spatial extent of highways. Conceptually, these capabilities will provide both maintenance contractors and highway agencies with robust tools to manage various aspects of PBRMC in an optimal manner. This will eventually lead to more efficient application of PBRMC at lower cost and higher LOS delivered to road users.

In order to demonstrate the capability of this system, a case study of an Egyptian highway will be considered. Particularly, Cairo- Ismailiyah highway was chosen for the development of the project-level IHAMS. On the other hand, five major highways were chosen for developing the network-level IHAMS. Accordingly, this research aims to achieve the following objectives:

1. Develop an integrated project-level PMS that optimizes the M&R action plan, taking into account the P/I system, to minimize the highway LCC.
2. Determine the most suitable KPIs' allowable limits and P/I system that enables the maintenance contractor to submit an acceptable M&R annual expenses and thus meet the highway annual budget.
3. Develop an integrated network-level PMS that is capable to obtain the optimum M&R action plan for a highway network, consisting of different highways with different KPIs' and P/I systems, in order to minimize the LCC and meet the network constraints (budget and overall condition).
4. Develop a GIS model, which acts as an alert system for the maintenance contractors to avoid paying any penalties and an visualization system for the highway agencies to better visualize the highway/network condition.

3.3 Research Methodology

The research methodology is inspired from several ideas that were integrated together to achieve the objectives. The research firstly began with an idea of applying PBRMC on an Egyptian case study. After reading extensive literature and compiling information on countries that have successfully applied PBRMC on their pavements, the author found that there was a missing area of study. Most of the literature was concentrating on either the PBRMC as a risk mitigation/transfer technique for highway agencies to reach higher LOS, or PMS as a more effective system for scheduling the M&R activities. From here came the idea of integrating both the PBRMC and PMS. Moving on throughout the study, the need for visualization was apparent. As a result, GIS was brought to attention with the purpose of a better spatial visualization model for the highway understudy, resulting in a better control for the highway expenditures. The author has conducted an extensive and detailed literature review on the following:

1. PBRMC and the vital KPIs' for the maintenance contractor assessment.
2. Existing P/I systems applied for PBRMC.
3. PMS main components (asset inventory, asset Inspection, pavement condition rating systems, pavement distresses, pavement deterioration models, future prediction deterioration models, pavement maintenance and rehabilitation strategies).
4. Optimization algorithms application on PMS.

Actually, this intensive literature review helped the author to investigate the existing systems, their strength and development points, and identify the area where to intervene with the aim of improving the overall system's efficiency. Afterwards, the study will define an adequate KPIs' and its P/I system to be applied on the intended study highway. Henceforth, the study will develop an asset inventory, which includes the most important aspects that need to be considered in the pavement study. At that juncture, the study will develop an inspection program that selects the optimal inspection percentage to guarantee a proper CI. Then, a future prediction deterioration model will be developed to forecast the condition at any point of time and reflect the

future applied maintenance on the pavement condition. Finally, a GIS model will be created to aid decision-makers in allocating the budget.

As shown in Figure 3-1 , the research passed through five consecutive phases. At the beginning, the initial idea was an application of PBRMC on the Egyptian pavements where; the author conducted literature review about successful applications of PBRMC in different countries. From the literature, the author realized that there was a missing link between PBRMC and PMS. Therefore, the author decided to change the scope from a contractual view of PBRMC to an integrated approach that combines PBRMC and PMS. Moving on with the data gathering, the author realized that the inspection plan and Actual Condition Rating System (ACRS) were imprecise and this leads to misleading results concerning the pavement condition. As a result, the author decided to develop an automated inspection and actual condition rating system that helps the local highway agencies in obtaining more accurate pavement condition. In addition, the author introduced the GIS as a visualization tool to better visualize the pavement condition.

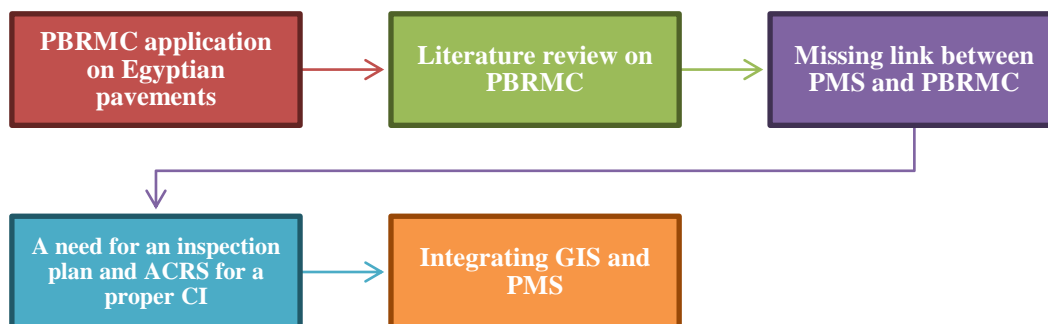


Figure 3-1: Research Methodology development phases

3.4 Need for P/I System for KPIs'

Due to the numerous number of KPIs', the need for a linked P/I system for the KPIs' was necessary for the evaluation of the maintenance contractors' performance. The highway agencies face a great problem in defining the KPIs' essential for assessing the maintenance contractors' performance throughout the contract period. In addition, they faced another problem in determining the value of the P/I for each KPI. Consequently, there is a great need for proper identification of the KPIs' as well as the determination of the P/I value for each KPI.

The need for P/I system for the KPIs' is the SMART missing bond between a theoretical (contractual) application of PBRMC on the PMS. Hence after, the P/I system is applied on the ACRS to assess and evaluate the maintenance contractors' performance throughout the contract period. In addition, the P/I system is applied on the future deterioration and maintenance module to enable the highway agencies calculate the future expenditures with meeting the pre-defined KPIs' limits. Figure 3-2 captures the missing bond (link) between the PBRMC and the PMS.

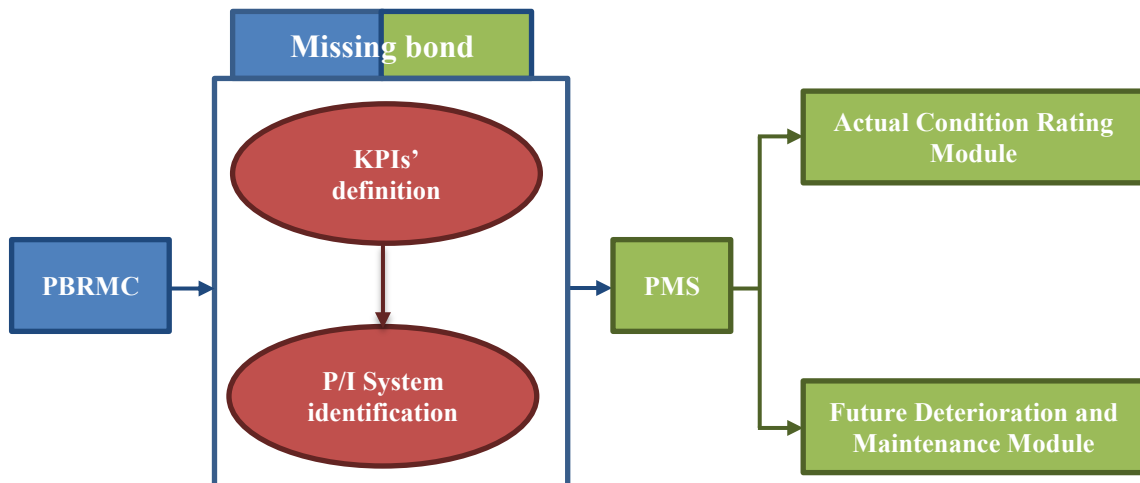


Figure 3-2: Need for P/I system for integrating the PBRMC and PMS

3.5 Need for Optimization

Due to the extremely large number of variables, the need for optimization took place with an objective of reaching a near optimal solution that meets the pre-defined targets. As shown in Figure 3-3, it could be tackled from four different perspectives as follows:

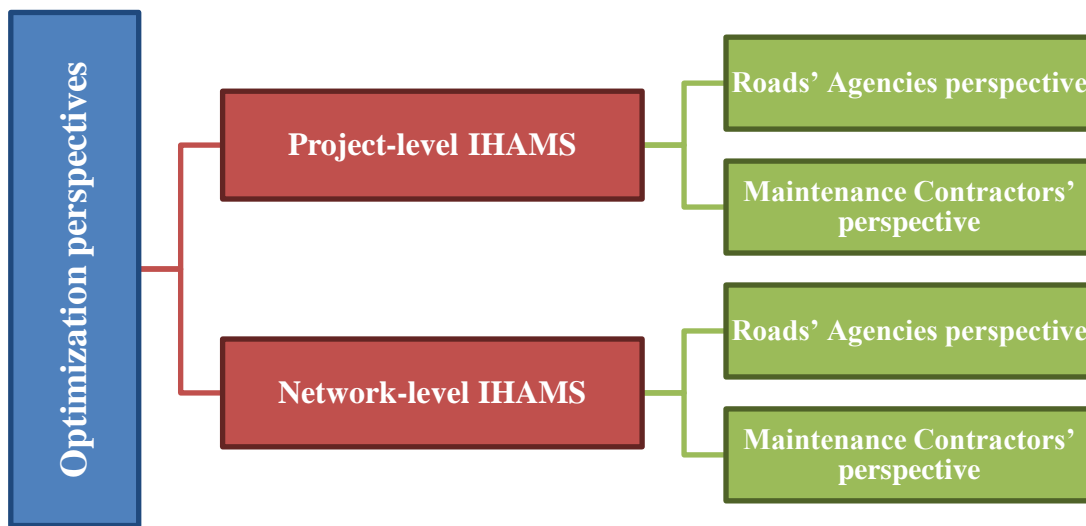


Figure 3-3: Optimization perspectives

3.5.1 Project-level IHAMS

3.5.1.1 Highway Agencies perspective

The need for optimization is necessary for the highway agencies to reach the following goals:

1. Obtain the near optimum inspection sample unit (%) that guarantees a proper CI and reflects the maintenance contractors' performance throughout the inspection period.
2. Develop a full P/I system that determines the KPIs' limits that should be met by the maintenance contractor within the contract period. In addition, it determines the bounded P/I

values that should be applied in the contract to enforce the maintenance contractor to meet a pre-defined level of standard.

3. Determine the annual maintenance budget to be allocated for each single pavement in order to meet the minimal level of service.

3.5.1.2 Maintenance Contractors' perspective

The need for optimization is essential for the maintenance contractors' to achieve the following goals:

1. Acquire the maintenance plan that both meets the KPIs' limits and minimizes the annual maintenance costs, given a pre-defined contractual P/I system.
2. Determine the optimal time to intervene, based on a developed KPIs' deterioration model, to minimize the overall maintenance costs throughout the contract period, without deviating from the pre-defined minimal level of service.

3.5.2 Network-level PMS

3.5.2.1 Highway Agencies perspective

The need for optimization is crucial for the highway agencies to attain the following goals:

1. Allocate the annual maintenance budget for the overall network from one side and for each pavement in the network from the other side based on the resulting maintenance plan, which meets the pre-defined level of service as well as the KPIs' limits, for each pavement.
2. Predict the annual maintenance budget for the overall network. This will act as a decision support tool that aid the

decision-makers to obtain a range for the available budget to build-up new pavements in the network.

3.5.2.2 Maintenance Contractors' perspective

The need for optimization is crucial for the maintenance contractors' to attain the following goals:

1. Predict the deterioration rate for each pavement in the network under his contractual obligation. In addition, the maintenance contractor could regularly compare the actual KPIs', resulting from the owners' assessment, and the predicted KPIs', resulting from the KPIs' deterioration model, to increase the accuracy of prediction.
2. Manage his available resources and expenditures spent on each pavement in the network with the purpose of meeting the pre-defined KPIs' limits, through placing timely constraints in the optimization model.
3. Apply the contractual P/I system of each pavement in the network, based on the ACR resulting from the owners' assessment, to evaluate his actual performance and take any corrective actions required to improve his maintenance performance.

In addition, Figure 3-4 shows the different research objectives that need to be optimally met. As shown in Figure 3-4, the research base is the integrated PBRMC and PMS where; the highway agencies and maintenance contractors are both willing to reach the optimum solution that:

1. Minimizes the LCC for the highway agency to improve the expenditures and maintain a larger number of highways annually.
2. Maximize LOS through improving the KPIs' allowable limits in which the maintenance contractor will have to spend more money and time in the maintenance of each highway.

3. Optimize the P/I system that obligates the contractor to meet the KPIs' rather than pay the penalty from one side and encourages him to improve the KPIs' to get the incentives from the other side.

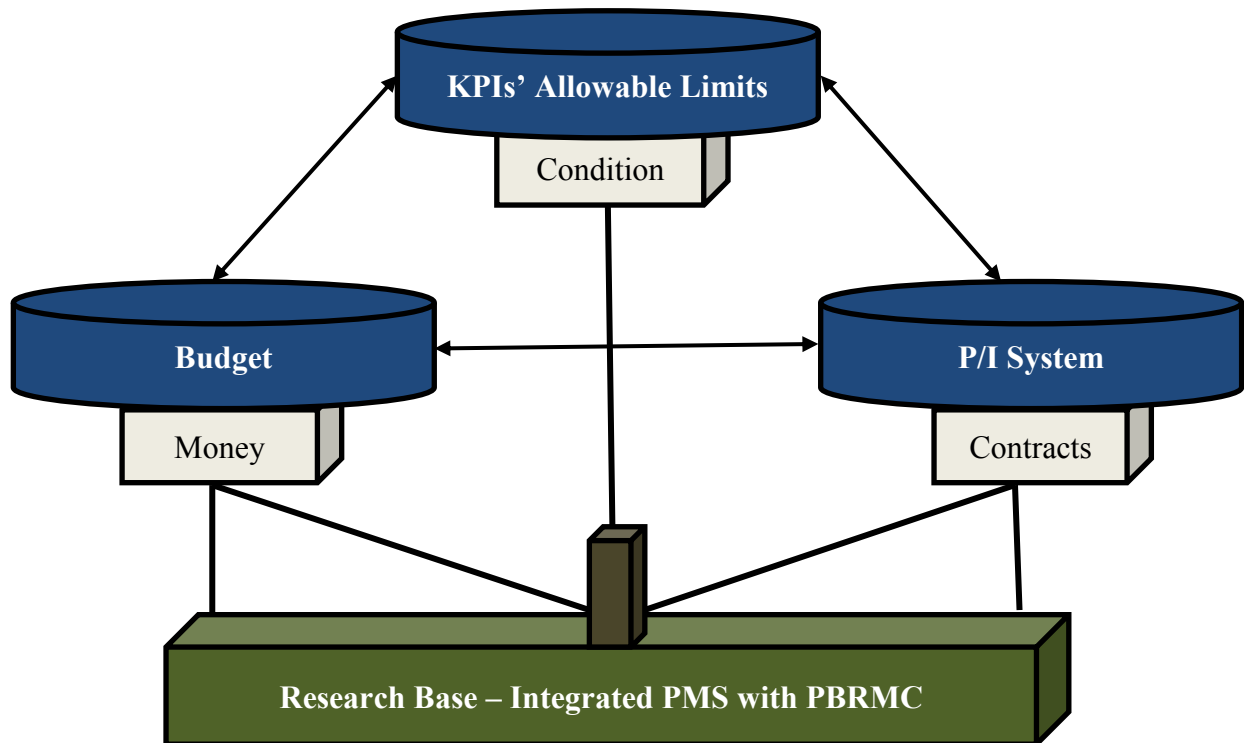


Figure 3-4: Research objectives base

3.6 Need for Visualization

The need for visualization was necessary for the highway agencies and the maintenance contractors to better track the highway/network LOS through a spatial map and take better decisions by then. In addition, it was obvious that a visualization tool (GIS) should be introduced to the PMS in order to precisely evaluate the maintenance contractors' performance based on the pre-defined KPIs'. The GIS will be the tool for achieving the following goals:

1. Improve the efficiency of expenditures which achieving an enhanced network condition.
2. Act as a visualization tool for the highway agencies and maintenance contractors to track the highway performance under the PBRMC and aids the maintenance contractors to take any quick corrective actions in order to avoid any penalties application.
3. Act as an evidence tool for the highway agencies to show, just in case of any arising claim for improper performance assessment, to the maintenance contractor as supplementary intelligent spatial attachments (inspection records).
4. Act as an intelligent spatial database for the pavements inside the same network. It includes all the segments' records for each pavement with KPIs' future prediction regularly updated from the future deterioration and ACR modules, based on the cut-off date.

3.7 Summary

Chapter three highlights the research methodology in depth. The research scope and objective were presented at the beginning to show its direct relation with the research methodology. In addition, the five research methodology development phases were pinpointed and explained in depth. Moreover, the need for P/I system for the KPIs' was clarified as well as the link between the PBRMC and PMS. Furthermore, the need for optimization for both the project-level and network-level PMS was elucidated from the highway agencies' and maintenance contractors' perspectives. Finally, the need for visualization was revealed with stating the main goals behind the visualization. The following chapter will be the "Research Framework".

4 CHAPTER 4 – RESEARCH FRAMEWORK

The focus of this research is to provide an IHAMS for PBRMC. PBRMC has shown to be an effective type of contracts for the road maintenance, resulting in high cost savings, ranging between 10% up to 30%, and meeting an acceptable LOS (Stankevich et al., 2009). It has been successfully applied in several countries where; it enhanced a better pavement condition as well as a safer travel for the end-users. In this research, the author aims to develop a decision-making support tool that integrates three disciplines to improve the highway asset management practices using PBRMC. The IHAMS is designed to support highway agencies in selecting an appropriate KPIs' and P/I system that guarantees an acceptable PCI and appropriate monthly expenses for the road M&R actions and therefore, it is capable to improve the efficiency of expenditures while achieving an enhanced LOS. In addition, the automated inspection program, functioning inside the IHAMS, gave the highway agencies the privilege to minimize their inspection costs, throughout the contractual period, by following the inspection rules and procedures, in order to guarantee a pre-defined CI from the maintenance contractors' performance. Furthermore, the flexibility of the IHAMS permits the maintenance contractors to search for the optimal M&R strategies that should be applied, throughout the contractual period, to meet the pre-defined contractual KPIs' and avoid any deviation from the main KPIs'.

4.1 Introduction

In this chapter, the research framework will be introduced and the different integrated modules will be discussed in details. The chapter begins with an introduction about the IHAMS and its' tangible benefits for both highway agencies and maintenance contractors. After that, the research framework for the project-level IHAMS and the network-level IHAMS will be highlighted and the three-integrated models structuring the system will be deliberated. Subsequently, the relationship between the different modules inside the models will be outlined in order to visualize how they are directly linked together to figure out the IHAMS. Finally, a detailed descriptive overview about each module, in both the project-level and network-level IHAMS, will be delivered with an illustrative screenshots from the system.

4.2 Research Framework

The IHAMS is an integrated highway asset management system that combines three different disciplines together to improve the highway asset management standards. The IHAMS could be divided into two different, but co-related, models:

1. Project-level IHAMS: It is the newly introduced in this study, which refers to the project-level PMS. It is managing one pavement system at a time with an objective of meeting the service quality of this certain pavement through the selection of the M&R actions at the optimum time.
2. Network-level IHAMS: It is the newly introduced term in this study, which refers to the network-level PMS. It is managing a network of pavements in a city with an objective of maximizing the overall network condition with limited financial resources.

Table 4-1 shows the summary of the project-level and network-level IHAMS modules.

Table 4-1: Project-level and Network-level IHAMS Modules

Project-Level IHAMS Modules	
Modules	Description
PLM-1: Central Database Module	It includes all the information about the asset attributes
PLM-2: Inspection Module	It includes the inspection plan and inspection sheet necessary for obtaining the actual condition
PLM-3: Actual Condition Rating Module	It includes the actual condition rating system used to assess the maintenance contractors' performance
PLM-4: Future Deterioration Module	It forecasts the pre-defined PBRMC KPIs' to run the optimization engine
PLM-5: Optimization Module	It features a GAs' engine to run the project-level IHAMS optimization scenarios
PLM-6: GIS Module	It is used for visualizing the highway condition

Network-Level IHAMS Modules	
Modules	Description
NLM-1: Project-level IHAMS Module	It includes all the modules referred above in the project-level IHAMS
NLM-2: Network Budgetary Module	It is used by highway agencies to define the network budget based on each highway budget and the required network and highways' KPIs'
NLM-3: Prioritization Module	It assigns weights for the highways in the same network
NLM-4: Optimization Module	It features a GAs' engine to run the network-level IHAMS optimization scenarios
NLM-5: GIS Module	It is used for visualizing the network condition

4.2.1 Project-level IHAMS

The project-level IHAMS functions through five-integrated modules, which link the three disciplines together in one complete management system, as follows:

1. Central Database Module
2. Inspection and Actual Condition Rating (ACR) Module
3. Future Deterioration Module
4. Optimization Module
5. User Interface and GIS Module

Figure 4-1 shows the project-level IHAMS framework and the direct relationship between the different modules. In addition, it provides a brief summary for each module to pinpoint the main idea and the link between the modules.

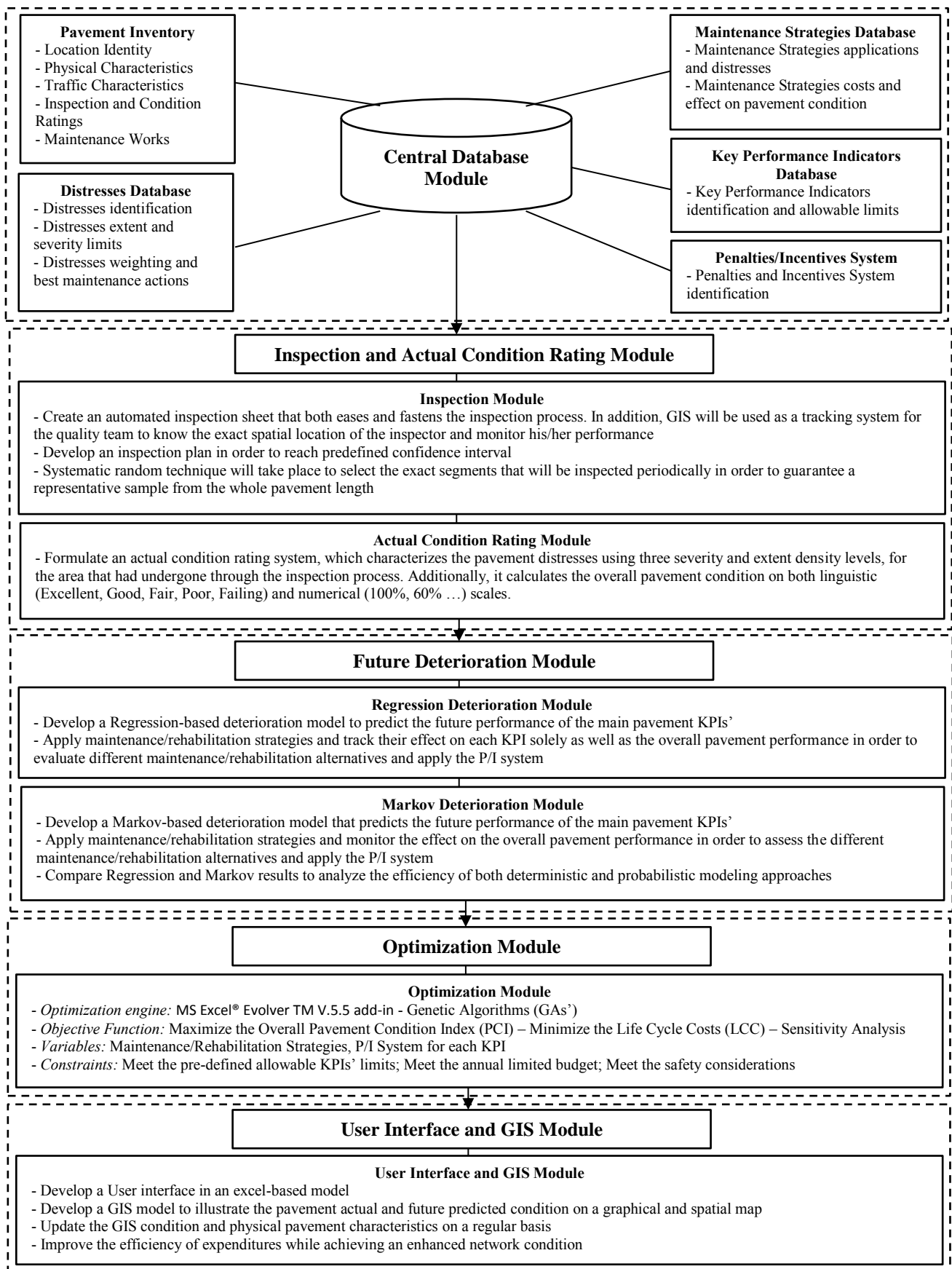


Figure 4-1: Project-Level IHAMS Framework

As shown in Figure 4-1, the project-level IHAMS functions through the above-mentioned five-integrated modules. The IHAMS initially begins with a central database module that consists of the following sub-modules:

1. Pavement Inventory: It consists of all the detailed descriptive attributes concerning the asset under the management of the IHAMS. It is a third-norm database consisting of five-linked data tables, as detailed in Appendix A – Pavement Inventory Description with a primary key for each table linked with an overall primary key, which is the unique location ID#.
2. Distresses Database: It is a list of the distresses types that affect the pavement within its' service life. It contains all the attributes concerned with each distress type such as; category, triggers and problems, measurement criteria and units, deterioration type, effect on the pavement, severity and frequency levels, weight, and deduction weights from the PCI.
3. M&R Strategies Database: It is a list of all the M&R strategies that could be applied on the pavements. It consists of all the attributes concerned with the M&R strategies such as; characteristics, optimum applied cases, preferable PCI to be applied, type, coverage, service life extension, and unit costs. In addition, it states the optimum M&R strategies for each distress type based on the severity and frequency tables defined on the distresses database.
4. KPIs' Database: It consists of a list of the defined contractual KPIs'. It consists of all the attributes that are necessary to assess the maintenance contractors' performance based on such as; KPI category, allowable limit, units of measurement.
5. P/I System: It consists of a list of the KPIs' and their allowable limits, as per defined in the KPIs' database, with the associated P/I values that are applied just in case of any deviation for the allowable limits. In addition, it consists of the P/I application criteria and condition (annually, per additional accident, etc...)

The system includes an inspection module where; the on-site inspector uses the generated inspection sheet in order to input the distresses values in the inspection segments. After finishing the inspection, the ACR module is the next step to evaluate the actual performance of the maintenance contractor, based on an automated ACR system, which translates the generated inspection sheet into a numerical KPI values, as will be detailed in section 4.3.3 - ACR Module, that represent the PCI of each segment and for the whole highway as well. The IHAMS developed two types of ACR modules namely; simple ACR module and detailed ACR module. The main difference between both is that the simple ACR module will force the on-site inspector to enter a numerical value for the surface rating including all the surface distresses. As a result, it mainly depends on the ability of the on-site inspector to match the actual surface rating with the pre-defined surface rating system.

Subsequently, the future deterioration module comes after obtaining the actual condition of the highway to forecast future condition and ratings for each KPI, which acts as a baseline for the current year condition for each single KPI as well as the PCI. The IHAMS developed two types of deterioration prediction models to compare their results and choose the deterioration prediction method to be addicted in this system. The first type was the Markov-chain deterioration model, which was conducted on a generic basis for the PCI using a five-condition matrix. The second type was the regression-based deterioration model, which was conducted in details to consider each KPI solely and calculate the annual PCI based on the predicted KPIs' conditions. The regression-based deterioration model showed a better results and control for the contractors' performance through each KPI. In addition, it provided the end-user with the advantage of comparing the detailed KPIs' results of IHAMS through the ACR and the regression-based deterioration model in order to minimize the percentage of error (%) and increase the prediction accuracy level for each KPI.

Then, the optimization module is introduced to support the highway agencies as well as the maintenance contractors' in their critical decisions. The IHAMS is designed to act flexibly to fit the needs of both the highway agencies and the maintenance contractors'. GAs' was chosen to be the optimization engine for its' strength in solving such a complex and multi-variable problems. The optimization

module functions through MS Excel® Evolver™ V.5.5 add-in as the running engine. The project-level IHAMS key objectives for the highway agencies could be summarized as follows:

1. Plan for the budget through predicting the future expenditures needed for the highway to keep it in an acceptable LOS. This is useful during the pre-bidding stage where; highway agencies can prepare a high-level cost estimate for the PBRMC and compare it with an existing cost for service delivery.
2. Determine appropriate KPIs' limits and P/I system, within the annual allowable highway budget, which allows the maintenance contractor to provide an acceptable monthly M&R expenses in the contract.
3. Conduct a sensitivity analysis (What-if Scenarios) by changing the KPIs' limits and P/I system to determine the impact on the LCC. This will enable the highway agencies to choose the optimal KPIs' and P/I system that fits their budget. In addition, this enables long-term planning concerning both the budget and LOS target setting. This will also enable highway agencies set up a well-informed discussion with road users about trade-offs between service levels and highway tolls in the case where; tolls are used to recover PBRMC costs.

In addition, the project-level IHAMS gives the maintenance contractors the ability to:

1. Select the optimal M&R action plan for a highway that both minimizes the LCC and meets the KPIs' limits.
2. Conduct a trade-off analysis for the cases of minimizing the LCC from one side and maximizing the highway condition from the other side.

Finally, a GIS model was developed to act as a visualization tool that supports the asset managers in their asset decisions. In addition, the GIS was also developed to:

1. Integrate the highway data through spatial technologies that links both the geographic data with the geometric and tabular data.
2. Support the maintenance contractors' in their critical M&R decisions through a GIS module that visualizes the highway condition (KPIs' and PCI) and acts as an alert system that warns them, based on both the current condition and the future deterioration rate, in case of any deviation from the KPIs' allowable limits as per defined in the contract.

Figure 4-2 shows the process flowchart for the project-level IHAMS where; it begins with a central database module where; the inputs are the pavement inventory, distresses database, M&R database, and KPIs' and P/I system. After that, it moves to the inspection module where; the generated inspection sheets are integrated with the inspection plan that defines the exact inspection samples, to act as an input for the ACR module to calculate the condition. On the other side, the future deterioration module is conducted for each KPI solely and, using the same criteria of the ACRS, the PCI is calculated from the predicted KPIs' results. After that, the financial module takes place to calculate the M&R costs (including the inflation rate %), P/I based on the defined criteria in the KPIs' and P/I system. Thereafter, the flexible optimization module takes place to run for the required objective as detailed above. Besides, a simple user interface and GIS were developed to enable the IHAMS users to obtain their results easily and act as both a visualization tool to support decision-makers in their critical decisions and a spatial database that integrates the geographic data with the geometric and tabular data.

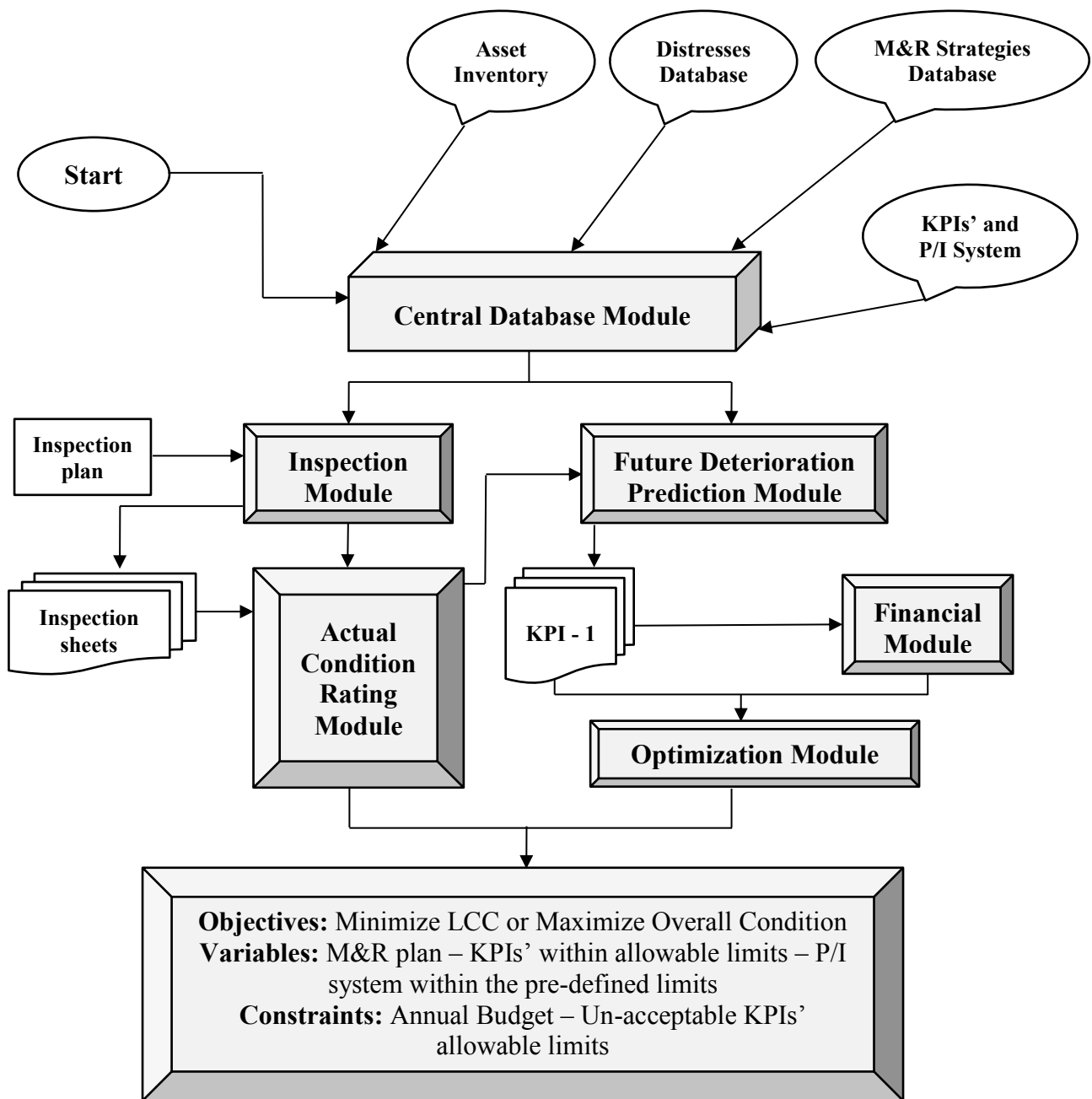


Figure 4-2: Project-level IHAMS Process Flowchart

4.2.2 Network-level IHAMS

The network-level IHAMS serves to extend the functionality of the project-level IHAMS by considering the need to allocate resources and manage multiple roadways simultaneously. Highway agencies need to have the ability to conduct a trade-off analysis for taking critical decisions about the expenditures distribution to be spent across different roadways depending on their relative importance. As such, different highways may have different KPI targets, and penalties and incentives built in to each contract. As such, this module allows the highway agency to manage multiple PBRMC simultaneously.

The network-level IHAMS functions through five-integrated modules, which links the three disciplines (PBRMC, PMS, GIS) together in one complete management system, as follows:

1. Project-level IHAMS Module (Including Central Database Sub-module, Inspection and ACR Sub-module, Future Deterioration Sub-module)
2. Network Budgetary Definition Module
3. Prioritization Module
4. Optimization Module
5. GIS Module

Figure 4-3 shows the network-level IHAMS framework and the direct relationship between the different modules. In addition, it schematically shows the direct integration between the project-level IHAMS and the network-level IHAMS, which will be explained in details later on in this chapter.

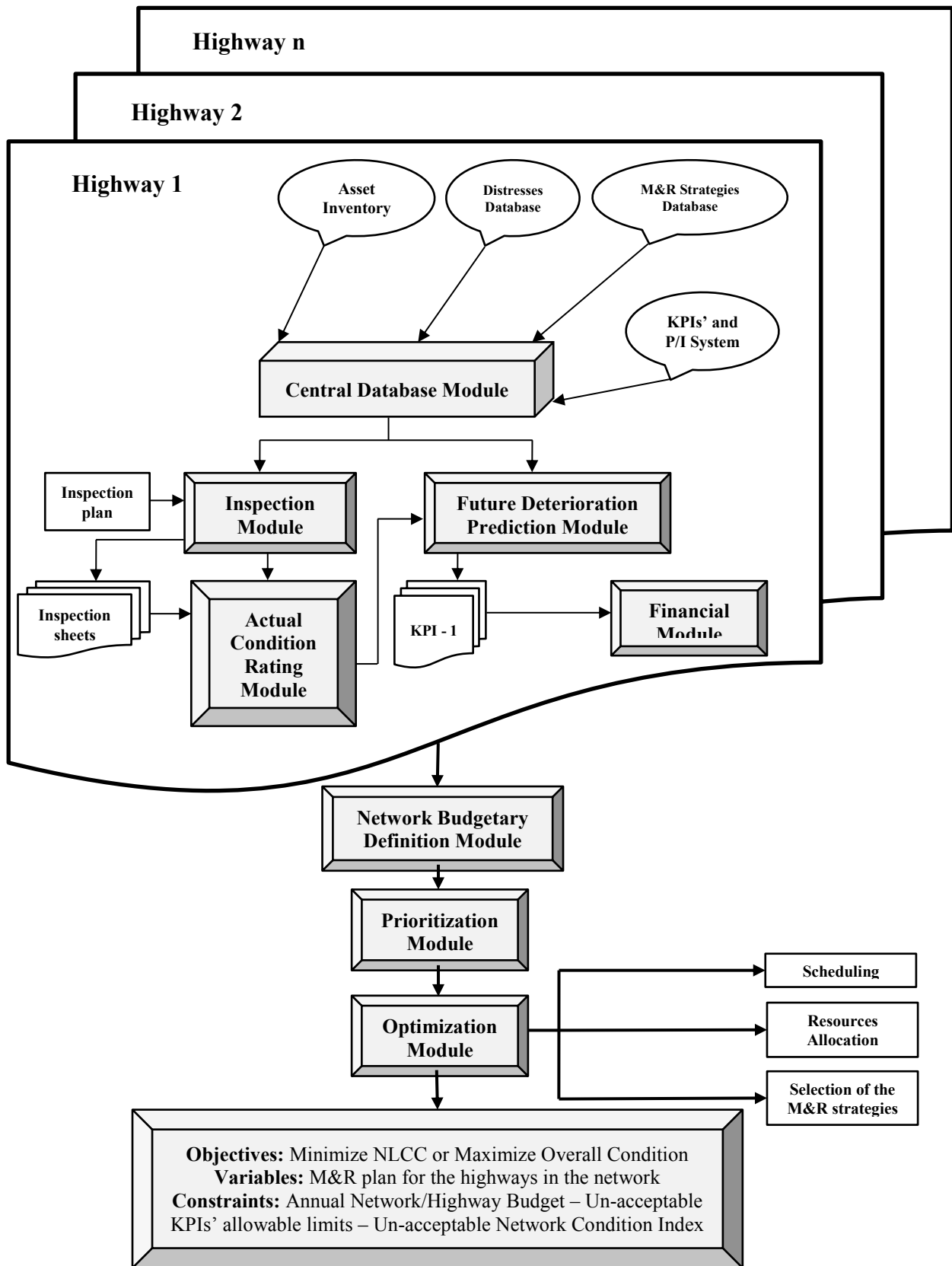


Figure 4-3: Network-level IHAMS Process Flowchart

As shown in Figure 4-3, the network-level IHAMS functions through the above-mentioned five integrated modules. Firstly, it begins with integrating all the highways within the network. The network-level budget is determined based on the summation of the M&R actions applied at the project-level IHAMS for each highway. This essentially provides the asset manager with a starting point for the budget needed to keep the highways in an acceptable condition. After that, the asset manager compares the available budget with the resulted budget to assign an annual budget for the network. Then, the prioritization module takes place to prioritize the highways in the networks, based on the importance of each highway (criticality, frequency, length, etc...). Thenceforward, the optimization module comes out to support the decision-makers, whether highway agencies or maintenance contractors, in their critical decision. GAs' was chosen to be the optimization engine for its' extreme strength in solving such a complex and multi-variable problems. The optimization module functions through MS Excel® Evolver TM V.5.5 add-in as the running engine. The network-level IHAMS key objectives for the highway agencies could be summarized as follows:

1. Plan for the network budget through predicting the future expenditures that are needed for each highway in the network to keep the highways within the network in an acceptable LOS.
2. Assign a high importance for a certain highway in the network to keep its' KPIs' within acceptable limits.

In addition, the network-level IHAMS gives the maintenance contractors the advantage to:

1. Schedule and choose the optimal M&R action plan for a network that both minimizes the LCC, aiming to reach a pre-defined budget limit, and meets the KPIs' limits.
2. Conduct a trade-off analysis for the cases of minimizing the LCC from one side and maximizing the Network Condition Index (NCI) from the other side.

3. Distribute their resources properly throughout the network. It gives the maintenance contractors the full control to assign a limiting constraint, representing the number of M&R activities that could be conducted annually, in order to avoid the application of any penalties due to not meeting the KPIs'.

Finally, a GIS model was developed to visualize the condition of each highway inside the network and the overall network, which assists the maintenance contractors' in their critical M&R decisions, acting as an alert system for them to optimally plan their M&R actions.

4.2.3 Integrated Project-level and Network-level IHAMS

The project-level IHAMS and the network-level IHAMS are integrated together to guarantee a proper overall network condition. Figure 4-4 describes the integration between both the project-level and network-level IHAMS.

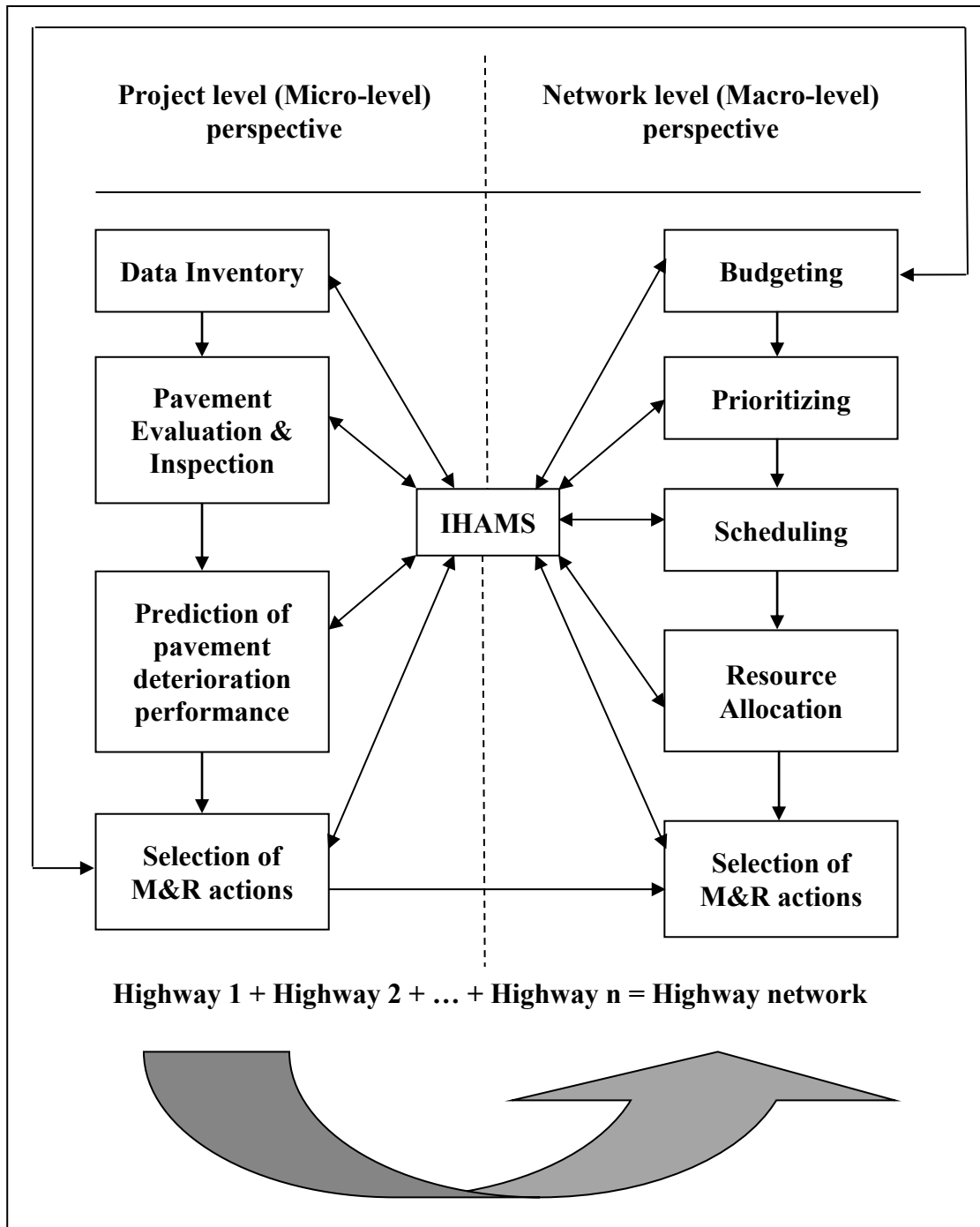


Figure 4-4: Integration between the project-level and network-level IHAMS

The definitions of the key network-level activities are as follows:

1. **Budgeting:** It is setting a certain budget for any M&R actions applied for this specific network.
2. **Prioritizing:** It is prioritizing the pavements in the network based on the importance of this pavement (criticality, frequency, etc...).
3. **Scheduling:** It is scheduling the M&R actions that need to be applied for each pavement. It is mainly conducted on a 5-year plan based on the budget set for this network and the pavement priority defined through a minimal service quality.
4. **Resource allocation:** It is allocating the financial/non-financial resources that are specified in the scheduling process.
5. **Selection of M&R actions:** It is the project-level IHAMS output for each pavement solely. As discussed previously for each pavement, the budget and a minimal service quality are determined from the network-level IHAMS. Afterwards, the project-level IHAMS runs to optimally choose the M&R actions required to meet both the pre-defined service quality and the allocated budget for this pavement.

As detailed in Figure 4-4, the process begins with defining allowable KPIs' limits for each highway in the network-level IHAMS. Then, the process continues in the project-level IHAMS where; the project-level IHAMS selects a proper M&R actions to be implemented on this highway in order to meet the pre-defined KPIs' allowable limits. Afterwards, the process continues with the network-level IHAMS where; it initially identifies a certain budget for each highway, based on both the selected M&R actions resulting from the project-level IHAMS and the available budget, and then sums up all the highways in the specified network to determine overall network budget to meet the agreed KPIs' limits. Thenceforth, planning and scheduling for the M&R actions, based on the annual available funds, takes place to end up with an annual budget for each highway. Subsequently, the process returns

once again to the project-level IHAMS to add the new annual budget constraint and select the M&R actions for each highway. Finally, the highways M&R actions are added up together to allocate the needed resources and bring out a 5-years plan for the M&R actions of the overall network.

4.2.4 Project-level and Network-level IHAMS users and benefits

The IHAMS is flexible in the way such the highway agencies and the maintenance contractors could benefit from. The IHAMS could be used by the highway agencies to:

1. Plan for the network/highway budget through predicting the future expenditures that are needed for the network/highway to keep the highway/network in an acceptable LOS.
2. Assign a high importance for a certain highway in the network to keep its' KPIs' within acceptable limits.
3. Formulate a logical KPIs' and P/I system, through an annual allowable budget for each highway, which allows the maintenance contractor to provide an acceptable monthly M&R expenses.
4. Conduct a sensitivity analysis (What-if Scenarios) by changing the KPIs' limits and P/I system with a 10% increments to track its' direct influence on the LCC. This will enable the highway agencies to choose the optimal KPIs' and P/I system that fits their budget. In addition, this will aid them to look forward to place a future target LOS and increase the budgetary limits for highway M&R.
5. Assess the maintenance contractors' performance through an automatic inspection and condition rating system, which begins from the distresses severity and extent level identification, moving to an inspection plan for the exact segments that needs to be inspected, and ends up with a condition rating system that provides the network/highway condition index based on the inspection results.

6. Integrate the network/highway data through spatial technologies that links both the geographic data with the geometric and tabular data.

In addition, the IHAMS gives the maintenance contractors the full opportunity to:

1. Select the optimal M&R plan for a network/highway that both minimizes the LCC and meets the KPIs' limits.
2. Conduct a trade-off analysis for the cases of minimizing the LCC from one side and maximizing the network/highway condition from the other side.
3. Distribute their resources properly throughout the network. It gives the maintenance contractors the full control to assign a limiting constraint, representing the number of M&R activities that could be conducted annually, in order to avoid the application of any penalties due to not meeting the KPIs'.
4. Assist the maintenance contractors' in their critical M&R decisions through a GIS model that visualizes the highway/network condition and acts as an alert system for them to optimally plan their M&R actions.

4.3 Project-level IHAMS Modules

The project-level IHAMS targets creating a full management system for a single highway. As discussed above, it functions through seven-integrated modules as follows:

1. Central Database Module
2. Inspection Module
3. ACR Module
4. Future Deterioration Prediction Module
5. Optimization Module
6. User Interface Module
7. GIS Module

In this section, each module will be discussed separately and the links between different modules will be highlighted.

4.3.1 Central Database Module

The central database module consists of the five sub-modules, linked together through a third- norm database form. The primary key for the asset inventory is the unique location ID #, which is linked with the other databases as will be discussed in the following modules:

4.3.1.1 Pavement Inventory

The pavement inventory consists of all the information necessary to define the highway including location, physical and traffic characteristics, historical inspection and condition rating, and past M&R actions. These datasets are linked through a third-norm with a one to many relationships. Figure 4-5 shows the direct relationship between the datasets with each other. Further details are discussed in Appendix A – Pavement Inventory Description.

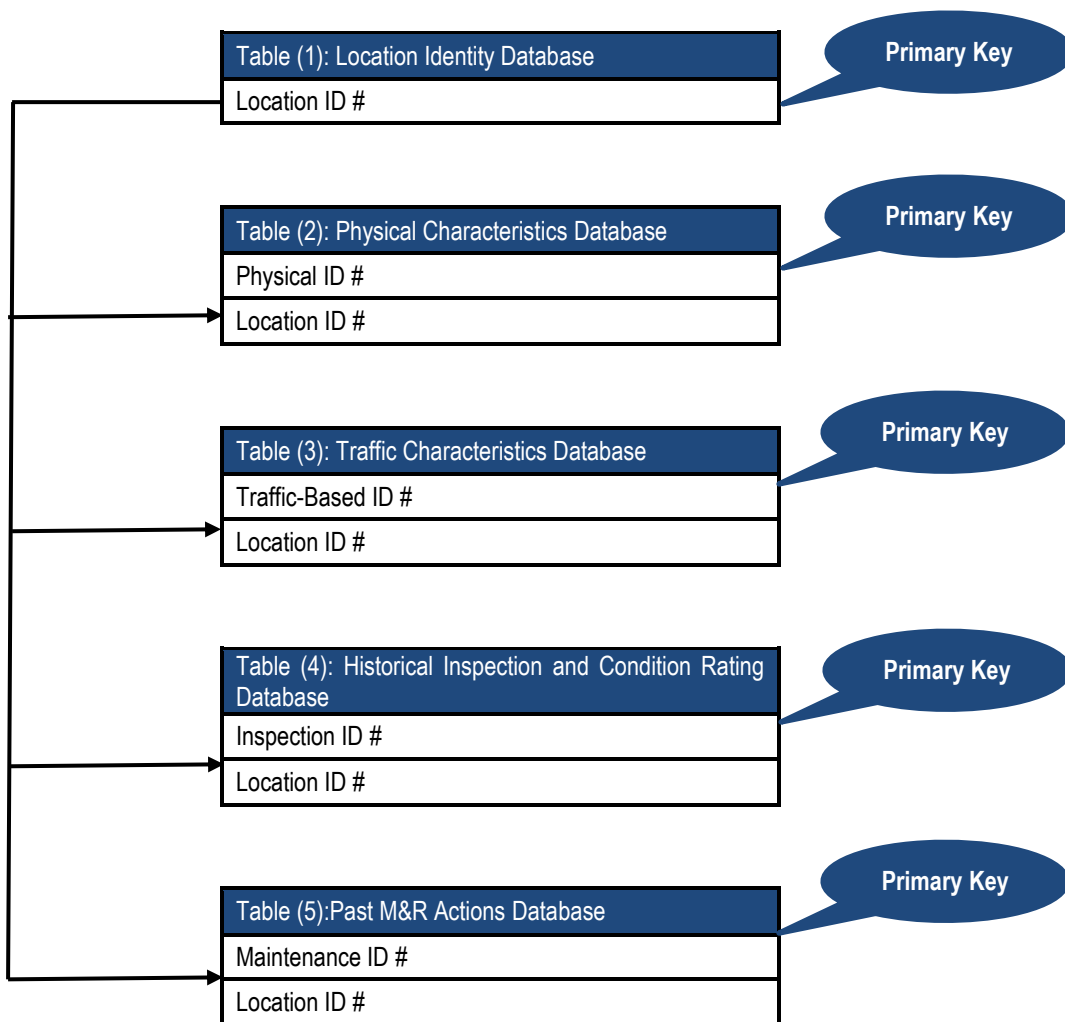


Figure 4-5: Relational database relationships

4.3.1.2 Distresses Database

The distresses database consists of all the information necessary to define the distress, the measurement criteria, the severity and extent levels of each distress, and the distress weight in the PCI calculation. Table 4-2 shows the information about the distresses, which includes the following attributes:

Table 4-2: Distress database attributes

Attribute Name	Description	Type/ Domain
Distress ID #	It is a unique ID # for each distress type.	Numeric
Distress type	It represents the type of the distress.	Text
Measurement units	It states the distress measurement units.	Text
Distress definition	It states the exact definition for each distress.	Text
Distress deterioration type	It represents distress deterioration type.	Look-up values (Fatigue, deformation)
Distress triggers	It states the triggers for each distress.	Text
Distress effect	It represents the effect of each distress.	Text
Distress weight (%)	It represents the weight of each distress on the overall PCI.	Numeric
Severity levels	It represents the different severity levels (low, moderate, and high) and the weights for each severity level.	*Varies (Text and Numeric)
Extent levels	It represents the extent of each distress (occasional, frequent, and extensive) and the weights for each extent level.	*Varies (Text and Numeric)

4.3.1.3 M&R Strategies Database

The M&R strategies database consists of all the information necessary to define the M&R strategies including the type, application conditions, unit cost, and effect on the KPIs'. Table 4-3 shows the information about the M&R strategies, which includes the following attributes:

Table 4-3: M&R strategies attributes

Attribute Name	Description	Type/ Domain
Maintenance ID #	It is a unique ID # for each maintenance record as more than a single maintenance could be applied for one segment.	Code
M&R type	It represents the applied M&R strategy.	Text
M&R definition	It states the application definition for each M&R strategy.	Text
M&R criteria	It states the M&R applicability criteria.	Text
Unit cost	It states the M&R strategy unit cost.	Numeric

4.3.1.4 KPIs' and P/I System

The KPIs' and P/I database consists of all the information necessary to define the KPIs' including the KPI units of measurement, KPI category, KPI allowable limit, and P/I system including the penalties and incentives values, application criteria and method for each KPI. Appendix B – Key Performance Indicators and Penalties/Incentives system introduced in the Performance-Based Road Maintenance Contract shows the contractual KPIs' and P/I system defined by IHAMS.

4.3.2 Inspection Module

The inspection module functions through a two-step formulation as follows:

1. Inspection Plan
2. Inspection Sheet

4.3.2.1 Inspection Plan

The inspection module begins with an inspection plan that determines the number of samples required for a pre-defined CI. In addition, the inspection plan features a “Systematic Random” engine that chooses the samples to be inspected randomly based on a randomized start and systematic intervals to guarantee a consistent overall highway PCI.

The first step in the inspection plan is calculating the Standard Deviation (SD or σ) of the whole population, based on previous inspection results. Then, the user inputs the required CI and the total number of samples in the population. Finally, the model calculates the number of samples and determines the samples that will be inspected based on the systematic random engine, which randomly selects a starting sample and an interval in which the samples will be passing through. In addition, Equation 4-1 and Equation 4-2 show the calculation procedures for the starting sample and the interval respectively. The main drawback in this approach is that sample units in failing condition may not necessarily be included in the survey. In addition, sample units that have a one-time-occurrence distress type may be included inappropriately as a random sample. In order to overcome these drawbacks, additional sample units are introduced to prevent extrapolation of unusual conditions across the entire highway.

Equation 4-1: Sampling Interval

$$\text{Sampling Interval } (i) = \frac{\text{Total number of samples } (N_s)}{\text{Number of inspection samples } (n)}$$

Equation 4-2: Random Start

$$\text{Random Start } (s) = \text{Randbetween}(1, i)$$

4.3.2.2 Inspection Sheet

The second step after determining the inspection samples is the inspection sheet. In this step, the on-site inspector takes the developed inspection sheet to fill on the data as per the inspection sheet, shown in Appendix C – Project-level IHAMS – Inspection Sheets. The inspection sheet was developed based on a number of several meetings with experts (GARBLT and separate maintenance contractors). In addition, it serves the ACR module to precisely calculate the segment PCI. The inspection sheet begins with general information about the highway under study, the segment, inspection details (Ref. pictures attached to the GIS, inspector name, inspection date, checking date, checker name). After that, it moves to the defects definition codes to assist the on-site inspector write-down the defects on the appended road plan with the actual defects. Finally, it consists of a summary table for the KPIs' that should be filled by the inspector after finishing each inspection sample.

4.3.3 ACR Module

The ACR module is categorized into two different sub-modules to fit the use and required accuracy level of the highway agency as follows:

4.3.3.1 Simple ACR Module

The simple ACR module is used to calculate the PCI, based on the inspection results. The four key categories used in the PCI calculation were as follows (NSYDOT, 2010):

1. Surface Rating (35%)
2. Alligator Cracking (15%)
3. Rutting Depth (15%)
4. IRI (35%)

The sum product of the weights and the inspection results in the PCI as shown in Equation 4-3. It is represented on a percentage scale and then translated into seven condition states namely (Excellent, Good, Fair, Poor, Very poor, Serious, Failing).

Equation 4-3: PCI calculator (NSYDOT, 2010)

PCI

$$= \{(35\% * \text{Surface rating}) + (15\% * \text{Alligator cracking}) + (15\% * \text{Rutting depth}) + (35\% * \text{IRI})\}$$

4.3.3.2 Detailed ACR Module

The detailed ACR module is used to calculate the PCI, based on the detailed results of the distresses inputted in the inspection sheets. The distresses weights are multiplied by the deduction values to calculate the PCI. The same equation applies with another criterion for the surface rating calculation, based on each distress extent and severity results not based on a certain simplified surface rating system.

4.3.4 Future Deterioration Prediction Module

The future deterioration prediction module was based on both:

1. Deterministic Approach → Regression-based prediction model
2. Probabilistic Approach → Markov-based prediction model

4.3.4.1 Deterministic Approach

4.3.4.1.1 General

The deterministic prediction approach was conducted using a regression-based model. The regression-based model is developed for the five-key KPIs' to aid the decision-makers, either the highway agencies or the maintenance contractors, in their critical decision concerning highway budget or M&R actions. These five KPIs' were certainly chosen to act as a base-line for comparing the future deterioration results with the actual condition rating results, following the same pattern for PCI calculation. Throughout this section, each KPI will be highlighted and the model formulation will be discussed. Further details about the results will be discussed in more details in the next chapter namely "Validation and Verification".

4.3.4.1.2 Model formulation description

The model begins with a general table that describes the highway characteristics, AADT, and the traffic growth rate as shown in Table 4-4. After that, a condition-rating system for each KPI is initiated as defined in the ACR module. Then, the KPI allowable limits and P/I system is extracted from the KPIs' and P/I system. The last step before developing the regression-based model is defining the KPIs' M&R strategies applicability index, which is a binary-based index to show whether the M&R strategy is applicable for improving a certain KPI or not, that improves its' performance. Finally, the regression model is developed, based on a deterministic equation, directly impacted by the age and the AADT.

The regression model begins with an age for the highway under study, based on the construction/re-construction year. Then, the regression model calculates the condition of each KPI, before applying any M&R strategic plan, by implementing Equation 4-4, Equation 4-5, Equation 4-6, Equation 4-7, and Equation 4-8 on the IRI, rutting depth, surface rating, alligator cracking and PCI respectively (Baoshan & Qiao, 2009).

Equation 4-4: IRI calculation

$$IRI_{in_i} = \{[(12.793 * N) + \langle(5.72 * 10^{-5} * AADT) * (1 + T)^N\rangle] * 0.057829\}$$

Equation 4-5: Rutting depth calculation

$$Rd_{in_i} = \{[(0.028 * N) + \langle(8.88 * 10^{-7} * AADT) * (1 + T)^N\rangle] * 25.4\}$$

Equation 4-6: Alligator cracking extent calculation

$$AG_{in_i} = \{[(0.025 * N^2) + (0.025 * N) + \langle(8.88 * 10^{-7} * AADT) * (1 + T)^N\rangle] * 1.27\}$$

Equation 4-7: Surface rating calculation

$$SR_{in_i} = \{ \{ [(5.6 * 10^{-3} * N^3) - (0.3454 * N^2) + (0.9952 * N) + (101.78)] - \langle(5.72 * 10^{-5} * AADT) * (1 + T)^N\rangle \} / 10 \}$$

Equation 4-8: PCI calculation

$$PCI_{in_i} = \{(0.35 * IRI_{in_i}) + (15\% * Rd_{in_i}) + (15\% * AG_{in_i}) + (35\% * SR_{in_i})\}$$

Where;

IRI_{in_i} is the annual initial IRI before applying any M&R strategy

Rd_{in_i} is the annual initial rutting depth before applying any M&R strategy

SR_{in_i} is the annual initial surface rating before applying any M&R strategy

AG_{in_i} is the annual initial alligator cracking before applying any M&R strategy

i is the number of years (age) counter

PCI_{in_i} is the annual initial PCI before applying any M&R strategy

N is the number of years (age) of the highway

T is the annual traffic growth rate (%)

$AADT$ is the annual average growth rate

After that, the regression model looks-up on the variables decision to implement the annual effect of the M&R applied strategy on each KPI as per Equation 4-9, Equation 4-10, Equation 4-11, Equation 4-12, Equation 4-13, and Equation 4-14 for the IRI, rutting depth, alligator cracking, surface rating, PCI and HCI respectively:

Equation 4-9: IRI after M&R action plan implementation

$$IRI_{cal_i} = \sum_j^{j=m} \{ [(12.793 * (Ap_j * X_{ij} * N)) + \langle (5.72 * 10^{-5} * AADT) * (1 + T)^{(Ap_j * X_{ij} * N)} \rangle] * 0.057829 \}$$

Equation 4-10: Rutting depth after M&R action plan implementation

$$\begin{aligned}
 & Rd_{cal_i} \\
 &= \sum_j^{j=m} \{ [(0.028 * (Ap_j * X_{ij} * N)) \\
 &+ \langle (8.88 * 10^{-7} * AADT) * (1 + T)^{(Ap_j * X_{ij} * N)} \rangle] * 25.4 \}
 \end{aligned}$$

Equation 4-11: Alligator cracking extent after M&R action plan implementation

$$\begin{aligned}
 & AG_{cal_i} \\
 &= \sum_j^{j=m} \{ [(0.025 * (Ap_j * X_{ij} * N)^2) + (0.025 * (Ap_j * X_{ij} * N)) \\
 &+ \langle (8.88 * 10^{-7} * AADT) * (1 + T)^{(Ap_j * X_{ij} * N)} \rangle] * 1.27 \}
 \end{aligned}$$

Equation 4-12: Surface rating after M&R action plan implementation

$$\begin{aligned}
 & SR_{cal_i} \\
 &= \sum_j^{j=m} \{ [[(5.6 * 10^{-3} * (Ap_j * X_{ij} * N)^3) \\
 &- (0.3454 * (Ap_j * X_{ij} * N)^2) + (0.9952 * (Ap_j * X_j * N)) \\
 &+ (101.78)] - \langle (5.72 * 10^{-5} * AADT) * (1 + T)^{(Ap_j * X_{ij} * N)} \rangle] / 10 \}
 \end{aligned}$$

Equation 4-13: PCI calculation

$$\begin{aligned}
 & PCI_{cal_i} \\
 &= \{ (0.35 * IRI_{cal_i}) + (15\% * Rd_{cal_i}) + (15\% * AG_{cal_i}) + (35\% * SR_{cal_i}) \}
 \end{aligned}$$

Equation 4-14: HCI calculation

$$HCI = \frac{\sum_{i=1}^n (PCI_{cal_i})}{N}$$

Where;

IRI_{cal_i} is the predicted IRI after M&R application

Rd_{cal_i} is the predicted rutting depth after M&R application

SR_{cal_i} is the predicted surface rating after M&R application

AG_{cal_i} is the predicted alligator cracking after M&R application

PCI_{cal_i} is the predicted PCI after M&R application

HCI is the overall highway condition index

j is the M&R strategies counter

m is the total number of maintenance strategies

n is the total number of contractual years

Ap_j is the applicability index (0 → Not Applicable (N/A) and 1 → Applicable)

X_{ij} is the decision variable resulting from the optimization engine where; it is represented on a numerical integers ranging from (0 → Do Nothing to m → total number of maintenance strategies)

As shown in the above equations, the regression model results in a newly calculated KPI condition after applying the M&R strategic plan. The equations above shows that the maintenance effect is directly proportional with the age, which is recalculated in the above formulas, taking the maintenance effect for each M&R strategy into consideration. Then, the model runs to get X_j for each year to reach the end-user objective as will be discussed later-on in the next section.

Finally, the financial module takes place to calculate the LCC, through-out the life-cycle time of the highway. The financial calculations are divided into the following sub-cost elements as follows:

1. Preventative maintenance costs (PRM)
2. Rehabilitation costs (RB)
3. Penalties (PEN)
4. Incentives (INC)

Each cost element is solely calculated, based on the pre-defined contractual criteria, to sum-up with the total LCC for the highway under the study. In the calculation, the NPV approach was applied for each cost element to consider the inflation effect on the M&R, penalties, incentives, and highway agencies budget. Equation 4-15, Equation 4-16, Equation 4-17, Equation 4-18, and Equation 4-19 show the calculation equation for each cost element and the total LCC.

Equation 4-15: Preventative maintenance costs

$$PRM_{total} = \sum_i^{i=n} \{(L_r * PRM_u) * (1 + in)^n\}$$

Equation 4-16: Rehabilitation costs

$$RB_{total} = \sum_i^{i=n} \sum_j^{j=m} \{(Ap_i * A_r * RB_{u_j} * X_{ij}) * (1 + in)^n\}$$

Equation 4-17: Penalties

$$PEN_{total} = \sum_i^{i=n} \sum_d^{d=r} \{(P_{u_d} * Ap_i) * (1 + in)^n\}$$

Equation 4-18: Incentives

$$INC_{total} = \sum_i^{i=n} \sum_d^{d=r} \{(Inc_{u_d} * Ap_i) * (-1) * (1 + in)^n\}$$

Equation 4-19: Life-cycle costs

$$LCC_{total} = \sum_i^{i=n} \{PRM_i + RB_i + PEN_i + INC_i\}$$

Where;

PRM_{total} is the total preventative maintenance costs

RB_{total} is the total rehabilitaiton costs

PEN_{total} is the total penalties as per defined in the contract

INC_{total} is the total incentives as per defined in the contract

LCC_{total} is the total LCC spent for this highway

L_r is the length of the road assigned for preventative maintenance

PRM_u is the unit cost for the preventative maintenance

i_n is the annual inflation rate (%)

A_r is the area of the highway assigned for M&R

Ap_i is the applicability index (0 → Not applicable (N/A), 1 → Applicable). It differs for each cost item based on the application criteria defined previously in the contract

RB_{u_j} is the unit cost for each rehabilitation strategy

d is the KPI calculator

r is the total number of KPIs' contracutually defined under the PBRMC

P_{u_d} is the penalty unit cost for each KPI solely

Inc_{u_d} is the incentive unit cost for each KPI solely

Finally, the regression model output is graphically represented to show:

1. The future condition before and after applying the M&R action plan.
2. The annual vs. cumulative costs spent for this KPI solely.
3. The preventative vs. rehabilitaiton costs spent for this KPI solely.
4. The applied penalties vs. incentives due to KPIs' meeting or deviation.

Table 4-4: General highway characteristics

General Assumption Items	Assumptions
Annual Inflation Rate (%)	8%
Pavement Characteristics Description	Pavement Characteristics
Total Pavement Length (Km)	200
Number of Lanes	4
Lane Width (m)	3
Total Pavement Area (m ²)	2,400,000
Average Annual Daily Traffic (AADT)	30,000
Percentage of Length for Preventive Maintenance (%)	5%
Length for Preventive Maintenance (Km)	10
Preventive Maintenance Area (m ²)	120,000
Percentage of Length to be crack sealed (%)	0.20%
Length to be crack sealed (Km)	0.4
Crack Sealing Area (m ²)	4,800
Percentage of Length to be slurry sealed (%)	0.20%
Length to be slurry sealed (Km)	0.4
Slurry Sealing Area (m ²)	4,800
Percentage of Length for micro-surfacing (%)	0.50%
Length for micro-surfacing (Km)	1
Micro-surfacing Area (m ²)	12,000
Percentage of Length to be overlaid (%)	0.80%
Length to be overlaid (Km)	1.6
Thin and Structural Overlay Area (m ²)	19,200
Percentage of Length to be patched (%)	0.40%
Length to be patched (Km)	0.8
Patching Area (m ²)	9,600
Percentage of Length for milling and filling (%)	0.50%
Length to be milled and filled (Km)	1
Milling and filling Area (m ²)	12,000
Percentage of Length to be Deep patched (%)	0.50%
Length to be Deep patching (Km)	1
Deep patching Area (m ²)	12,000
Percentage of Length to be reconstructed (%)	0.50%
Length to be reconstruction (Km)	1
Reconstruction Area (m ²)	12,000
Traffic Growth Rate (%)	5%

4.3.4.2 Probabilistic Approach

4.3.4.2.1 General

As an alternative to the deterministic modeling approach, a markov-based deterioration model was developed for predicting both the future IRI and PCI. While using Markov-based models, it is necessary to calculate the length of the highway in each condition state on a time series data. One of the advantages of the markov-based deterioration model is that it captures the uncertain deterioration behavior of pavements. The concept of Markov-based deterioration process is presented in Figure 4-6.

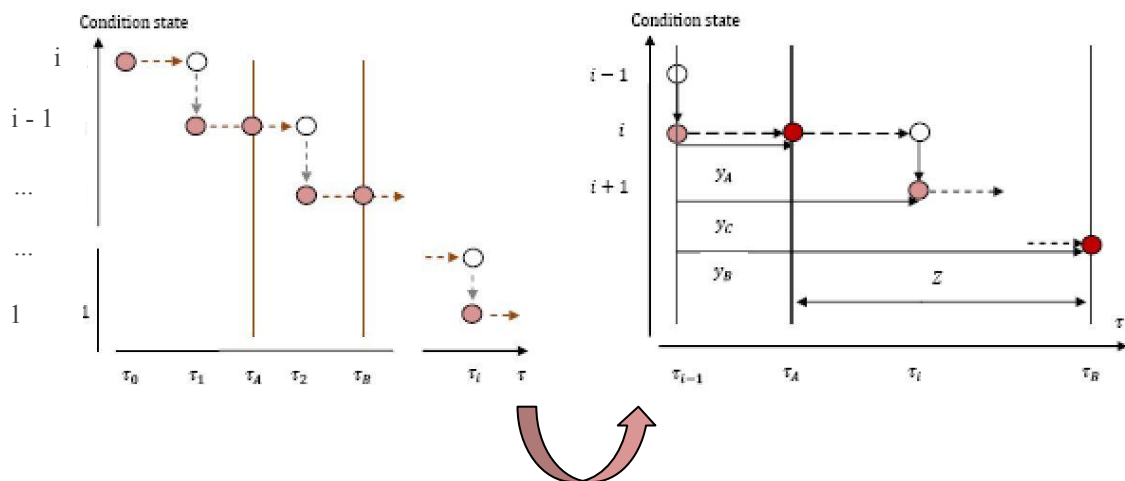


Figure 4-6: Markov deterioration process (Suharman, 2012)

In Figure 4-6, r represents real calendar time. The deterioration of the pavement begins immediately after it is exposed to the public at time r_0 . The condition state of an asset is expressed by a rank representing a state variable ($i = i, i - 1, \dots, 1$). For a component in the excellent situation, its condition state is given as $i = i$, and the decrease in the pavement condition state expresses progressing deterioration. A value of $i = 1$ indicates that a component has reached its service limit. In this figure, for each discrete time τ_i ($i = i, \dots, J - 1$) on the time-axis, the corresponding condition state has increased from i to $i + 1$. Hereinafter τ_i is referred to the time a transition from a condition state i to $i + 1$ occur.

The probabilistic Markov-model was applied only on two KPIs', PCI and IRI, due to the availability of valuable data to be able to base our model on, and compared with the deterministic regression-based model. The condition states were transformed from a numerical values, either 0 to 100 for the PCI or 0 to 5 for the IRI, to a 5-condition states to act as a baseline for comparing the two future predication models.

4.3.4.2.2 Model formulation description

Similar to the regression-based model formulation, the markov-based model utilizes generic highway input data as shown in Table 4-4. Afterwards, the Markov model is developed, based on the original transition-matrix as shown in the below matrices.

Condition	Excellent	Good	Fair	Poor	Failing
Excellent	P_1	$(1 - P_1)$	0	0	0
Good	0	P_2	$(1 - P_2)$	0	0
Fair	0	0	P_3	$(1 - P_3)$	0
Poor	0	0	0	P_4	$(1 - P_4)$
Failing	0	0	0	0	1

Matrix 4-1: Original Transition Probaility Matrix (OTM)

Condition	M&R %
Excellent	0
Good	0
Fair	X_1
Poor	X_2
Failing	X_3

Matrix 4-2: M&R action plan matrix - Decision Variables

Curent Condition	Excellent	Good	Fair	Poor	Failing
	C_1	C_2	C_3	C_4	C_5

Matrix 4-3: Current Condition matrix (CCM)

Condition	Excellent	Good	Fair	Poor	Failing
Excellent	P_1	$(1 - P_1)$	0	0	0
Good	0	P_2	$(1 - P_2)$	0	0
Fair	X_1	0	$[(1 - X_1) * P_3]$	$1 - \{X_1 + [(1 - X_1) * P_3]\}$	0
Poor	X_2	0	0	$[(1 - X_2) * P_4]$	$1 - \{X_2 + [(1 - X_2) * P_4]\}$
Failing	X_3	0	0	0	$1 - X_3$

Matrix 4-4: New Transition Matrix (NTM)

Where;

OTM is the original transition probability matrix

CCM is the current condition matrix

NTM is the new transition matrix

P_i is the annual probability that the highway will be in this condition state

i is the number of years (age) counter

c is the condition state counter (Excellent, Good, Fair, Poor, Failing)

X_c is the M&R percentage chosen by the optimization engine to meet the KPIS' and meet the objective

C_c is the current percentage of the highway length for each condition state

After that, the matrix-add-in was applied to the markov-based model in order to be able to calculate the length of the highway in each condition state using the following equations:

Equation 4-20: Annual Probability Matrix (PM)

$$Probability\ Matrix_i (PM_i) = M_{pow}(NTM, i)$$

Equation 4-21: Annual Condition Matrix (CM)

$$Condition\ Matrix_i (CM_i) = MMULT(PM_i, CCM)$$

Equation 4-22: Annual Highway Length for each condition state

$$Highway\ Length_{ic} (HL_{ic}) = CM_i * Highway\ Length (HL)$$

Where;

PM_i is the annual probability matrix

CM_i is the annual condition matrix

HL_{ic} is the annual highway length for each condition state (c)

Similar to the deterministic approach, the financial module takes place to calculate the preventative maintenance and rehabilitation costs, based on the condition state rehabilitation percentage, strategy unit cost, and resulting length or area. Finally, the P/I system was applied to obtain the overall highway LCC.

Equation 4-23: Rehabilitation costs

$$RB_{total} = \sum_i^{i=n} \sum_c^{c=f} \{ (HL_{ic} * RB_{u_j}) * (1 + in)^n \}$$

Where;

n is the total number of contractual years

f is the total number of condition states

RB_{u_j} is the unit cost for each rehabilitation strategy

in is the annual inflation rate (%)

4.3.5 Optimization Module

The optimization module integrates the KPIs' deterioration results and M&R effects. The system can provide benefits for both highway agencies and maintenance contractors under PBRMC through addressing the following scenarios, as shown in Table 4-5:

Table 4-5: Project-level scenarios description

Scenario #	Name	Description
Scenario 1	Highway budget definition	Highway agencies can schematically determine the highway budget in the pre-bidding phase
Scenario 2	Highway KPIs' and P/I definition	Highway agencies can determine the optimum KPIs' allowable limits and P/I system that meets a certain budget
Scenario 3	Sensitivity Analysis	Highway agencies can track the effect of increasing the KPIs' allowable limits on the contractual LCC
Scenario 4	LCC Minimization	Maintenance contractors can obtain the optimum M&R action plan to reach a minimal LCC and meet the KPIs' unacceptable limits
Scenario 5	Trade-off Analysis	Maintenance contractor can achieve a better LOS with a minimal LCC by applying goal optimization approach

The optimization formulation sheet fits the different scenarios to act as a flexible system, providing different users with the opportunity to choose their own objectives and variables, and place their own constraints, that aid decision makers to achieve their own goals (maximize the HCI and minimize LCC). As shown in Figure 4-7, the optimization formulation passes through four main stages as follows:

1. Definition stage

2. Formulation stage
3. Optimization stage
4. Tracking stage

The definition stage begins with defining general assumptions, pavement characteristics and the KPIs' distribution to calculate the PCI. Then, it moves to the second part, which is the KPIs' and P/I system definition where; it automatically obtains the information from the KPIs' database and P/I system defined earlier on this chapter. Finally, it moves to the third part, which is the M&R definition and applicability on the KPIs'.

Moving towards the next stage, which is the formulation stage. It begins with a constraint formulation that formulates the constraints check for the different KPIs' where; it provides the user with a colored cell, either red for not meeting the constraint or green for successful meeting the constraint, detailing both the annual status of each KPI and the budget status as well. Then, the variable and objective function formulation takes place in the optimization stage.

The third stage is the optimization stage. This is the key stage that links the inputs and outputs. The results of the optimization stage, represented by M&R action plan or KPI's and P/I system, are the decision variables for the project-level IHAMS. The optimization engine features the MS Excel® Evolver V.5.5 add-in, and uses the GA optimization option. The different optimization scenarios are defined later on this chapter.

Finally, the fourth and last stage is the tracking stage. An automated KPIs' sheet was created to summarize the effect of the chosen M&R action plan or P/I system on the pavement under study. In addition, it helps the end-user in tracking the results easily and taking corrective actions if necessary.

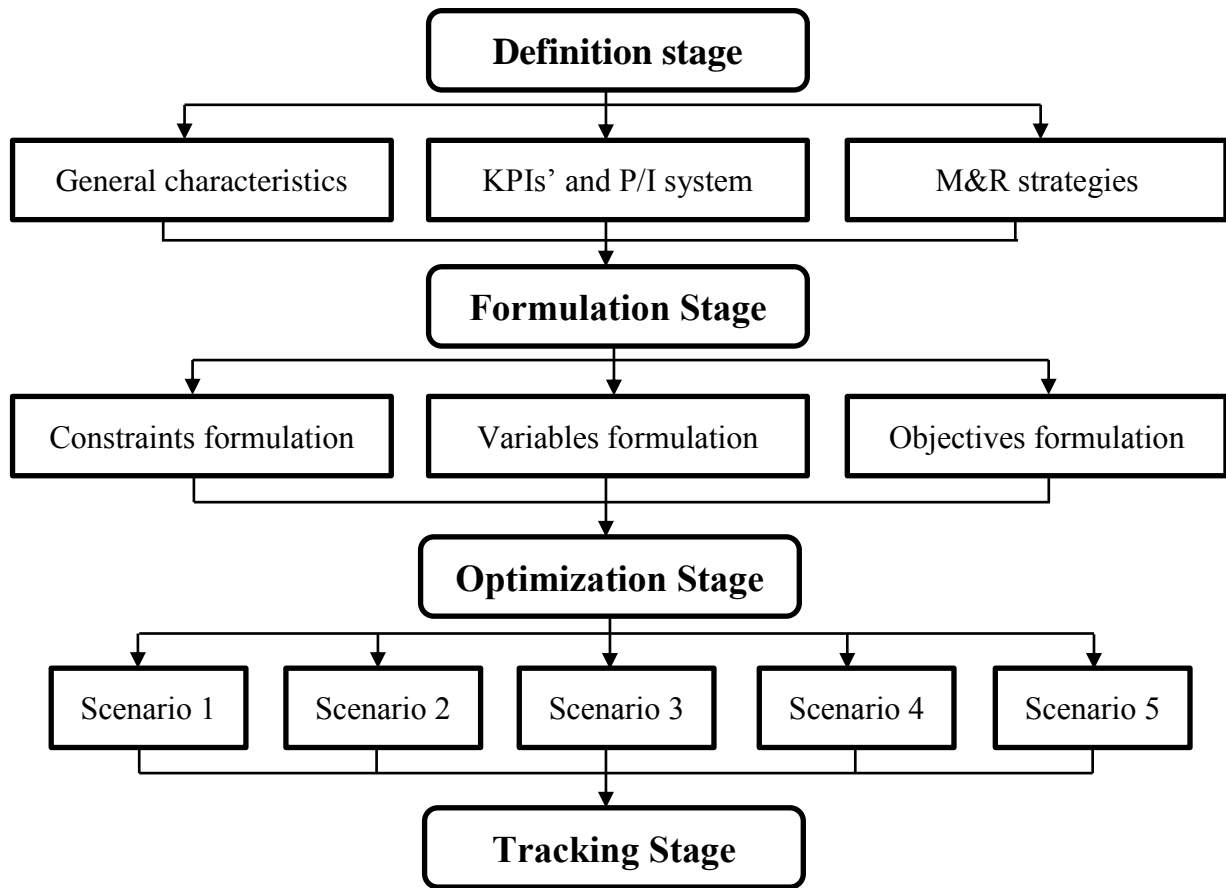


Figure 4-7: Project-level optimization formulation flowchart

4.3.5.1 Scenario 1 - Highway Budget Definition

This scenario is mainly for the highway agencies to assign an acceptable budget for the highways. Table 4-6 shows the main attributes for this scenario.

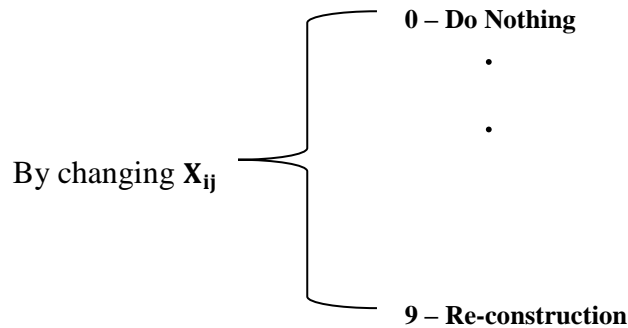
Table 4-6: Scenario 1, 3 and 4 project-level optimization attributes

Attribute	Description
Objective Function	Minimize highway LCC within the contract period <i>Minimize LCC_{total}</i>
Variables	Highway M&R action plan - X_{ij}
Constraints	<ul style="list-style-type: none"> ➤ PCI hard constraint ➤ IRI hard constraint ➤ Rutting depth hard constraint ➤ Surface rating hard constraint ➤ Alligator cracking extent hard constraint

As discussed in Table 4-6, the optimization attributes could be mathematically formulated as follows:

Equation 4-24: Objective function

$$\text{Minimize } LCC_{total}$$



Where;

Table 4-7 shows the decision variables and their corresponding maintenance strategies that were considered in the IHAMS.

Table 4-7: Decision variables

X_{ij}	Decision Variable ID #	Maintenance Strategies
X_0	0	Do Nothing
X_1	1	Crack Sealing
X_2	2	Slurry Sealing
X_3	3	Micro-surfacing
X_4	4	Thin Overlay
X_5	5	Structural Overlay
X_6	6	Patching
X_7	7	Milling and filling
X_8	8	Deep patching
X_9	9	Reconstruction

Subject to the following constraints:

Equation 4-25: Annual PCI constraint

$$PCI_{cal_i} < PCI_{LT}$$

Equation 4-26: Overall highway condition index constraint

$$HCI < PCI_{LT}$$

Equation 4-27: Annual Surface rating constraint

$$SR_{cal_i} < SR_{LT}$$

Equation 4-28: Annual IRI constraint

$$IRI_{cal_i} < IRI_{LT}$$

Equation 4-29: Annual Alligator cracking constraint

$$AG_{cal_i} < AG_{LT}$$

Where;

PCI_{LT} is the PCI hard constraint in which the annual PCI and the overall HCI resulting from the M&R action plan couldn't exceed

SR_{LT} is the surface rating hard constraint in which the surface rating resulting from the M&R action plan couldn't exceed

IRI_{LT} is the IRI hard constraint in which the IRI resulting from the M&R action plan couldn't exceed

AG_{LT} is the alligator cracking hard constraint in which the alligator cracking resulting from the M&R action plan couldn't exceed

The constraint formulation provides the user with a binary-based coding (0 and 1), which are translated into a colored cell, either red for not meeting the constraints or green for successful meeting the constraints, detailing both the annual status of each KPI and the budget status.

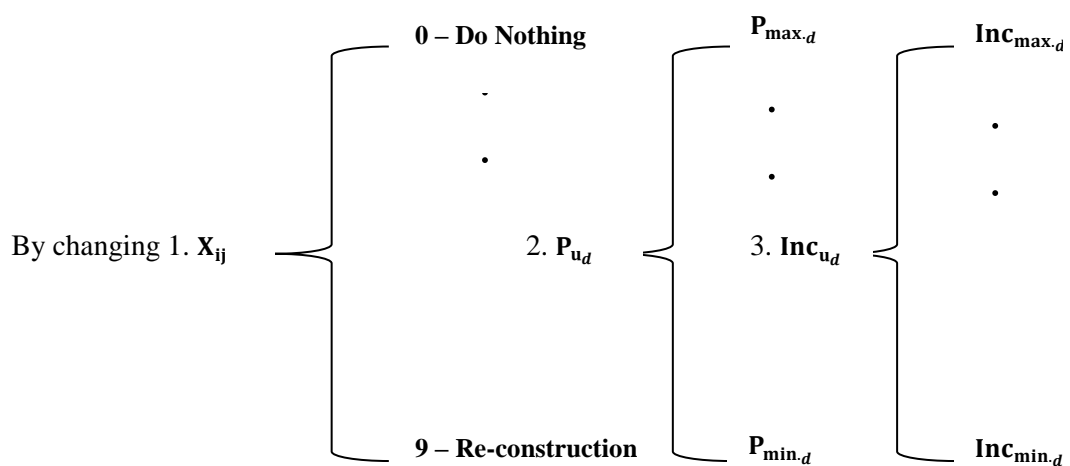
4.3.5.2 Scenario 2 – Highway KPIs' and P/I System Definition

This scenario aids the highway agencies in preparing the PBRMC KPIs' and P/I system, which both enforces the maintenance contractors to meet the pre-defined contractual limits and guarantees a proper LCC for the maintenance contractor to accept the contractual obligations. Table 4-8 shows the main attributes for this scenario.

Table 4-8: Scenario 2 project-level optimization attributes

Attribute	Description
Objective Function	Minimize highway LCC within the contract period <i>Minimize LCC_{total}</i>
Variables	<ol style="list-style-type: none"> 1. Highway M&R action plan - X_{ij} 2. Highway KPIs' allowable limits 3. Highway P/I system - P_{ud} and I_{ud}
Constraints	<ul style="list-style-type: none"> ➤ Annual budget constraint ➤ PCI hard constraint ➤ IRI hard constraint ➤ Rutting depth hard constraint ➤ Surface rating hard constraint ➤ Alligator cracking extent hard constraint ➤ KPIs' allowable minimum and maximum limits ➤ P/I minimum and maximum defined limits

As discussed in Table 4-8, the optimization attributes could be mathematically formulated as scenario 1 with different variables as follows:



Where;

$P_{max,d}$ is the maximum penalty limit for each KPI chosen by the user

$P_{\min,d}$ is the minimum penalty limit for each KPI chosen by the user

$Inc_{\max,d}$ is the maximum incentive limit for each KPI chosen by the user

$Inc_{\min,d}$ is the minimum incentive limit for each KPI chosen by the user

4.3.5.3 Scenario 3 – Sensitivity Analysis

This is a sensitivity analysis conducted to give the highway agencies the opportunity to track the direct effect of incrementally increasing the KPIs' allowable limits and the P/I system on the KPIs' from one side and on the LCC from the other side. It also allows the highway agencies to inform the highway users with the budget increase for reaching a better LOS. The sensitivity analysis will be discussed in section 5.1.1.3.3.2 - Scenario 2 – Sensitivity analysis.

4.3.5.4 Scenario 4 – LCC Minimization

This scenario targets the maintenance contractors to implement the optimum M&R action plan with a given KPIs' allowable limits and P/I system throughout the contract period. The main difference between scenario 4 and scenario 1 is the added constraint for the annual budget represented mathematically as follows:

Equation 4-30: Annual budget constraint

$$LCC_i < HBT_i$$

Where;

HBT_i is the annual highway budget constraint. The NPV equations are applicable where; $HBT_n = HBT_1 * (1 + in)^n$

4.3.5.5 Scenario 5 – Trade-off Analysis

This scenario features a goal optimization with an attempt for the maintenance contractor to reach a better M&R action plan with a better LOS and gain higher incentives by then. Table 4-9 shows the main attributes for this scenario.

Table 4-9: Scenario 5 project-level optimization attributes

Attribute	Description
Objective Function	<p>Minimize HCI and LCC Deviation</p> $\text{Minimize } DEV_{total} = \left(\frac{LCC_{total} - LCC_{limit}}{LCC_{limit}} + \frac{HCI_{limit} - HCI}{HCI_{limit}} \right)$
Variables	Highway M&R action plan - X_{ij}
Constraints	<ul style="list-style-type: none"> ➤ Annual budget constraint ➤ PCI hard constraint ➤ IRI hard constraint ➤ Rutting depth hard constraint ➤ Surface rating hard constraint ➤ Alligator cracking extent hard constraint

As discussed in Table 4-9, the optimization attributes could be mathematically formulated as scenario 4 with different objective function as follows:

Equation 4-31: Project-level trade-off objective function

$$\text{Minimize } DEV_{total} = \left(\frac{LCC_{total} - LCC_{limit}}{LCC_{limit}} + \frac{HCI_{limit} - HCI}{HCI_{limit}} \right)$$

Where;

DEV_{total} is the total budget and condition deviation

LCC_{limit} is the total budget required for the highway under study

HCI_{limit} is the minimum allowable highway condition index that could be reached even after applying the P/I system

4.3.6 GIS Module

The GIS module was developed for the following motives:

4.3.6.1 Geographic Data Integration

The GIS will act as an intelligent spatial database for the segments within the same highway. It includes all the segments' records for each pavement with KPIs' future prediction regularly updated from the future deterioration and ACR modules, based on the cut-off date.

4.3.6.2 Highway KPIs' Alert System

The GIS acts as an alert system that notifies both the highway agencies and maintenance contractors with any deviations, either in the KPIs' or in the overall PCI, taking place or going to take place, based on the future deterioration project-level IHAMS results.

4.4 Network-level IHAMS Modules

The network-level IHAMS targets creating a full management system for a network of highways. As discussed above, it functions through six-integrated modules as follows:

1. Project-level IHAMS Module
2. Network Budgetary Definition Module
3. Prioritization Module
4. Optimization Module
5. User Interface Module
6. GIS Module

In this section, each module will be discussed separately and illustrative screenshots will be highlighted for better visualization.

4.4.1 Project-level IHAMS Module

The project-level IHAMS module is the base line for the network-level IHAMS as the aim of the network-level IHAMS is to integrate the highways under the network in one combined model to be able to track the overall network KPIs' and the separate highway KPIs' after applying the M&R action plan. The project-level IHAMS includes the following sub-modules:

1. Central Database Module
2. Inspection Module
3. ACR Module
4. Future Deterioration Module

The details about these sub-modules were discussed in the previous section namely "Project-level IHAMS Modules".

4.4.2 Network Budgetary Module

The network budgetary module is defined based on the results, achieved from the combined future deterioration results of the project-level IHAMS module, to provide the asset manager with an idea about the budget needed to keep the highways in an acceptable condition. After that, the asset manager compares the available budget with the resulted budget to assign an annual budget for the network. This module directly depends on the results of the project-level IHAMS module as detailed earlier on this chapter in Figure 4-4. It is the main link between the project-level IHAMS and the network-level IHAMS where; the results of the project-level IHAMS are the preliminary budget constraint for the network-level IHAMS. After that, the asset manager compares the available budget with these results to be able to allocate an acceptable budget for the network. Equation 4-32 shows the calculation of the network budget from the project-level IHAMS LCC for each highway.

Equation 4-32: Network budget calculation

$$NTB = \sum_k^{k=h} \sum_i^{i=n} (LCC_{total_{i_k}})$$

Where;

NTB is the network budget

k is the number of highways counter

h is the total number of highways

4.4.3 Prioritization Module

The prioritization module takes place to prioritize the highways in the networks, based on the importance of each highway (criticality, frequency, length, etc...). In this study, the prioritization weights were based on the highway length, the longer the highway length, the more critical its' effect will be on the network condition.

4.4.4 Optimization Module

The optimization module combines the future deterioration results of the project-level IHAMS module with the controlling budget constraint through prioritization weights for each highway, based on the highway length, in a single optimization formulation sheet, to result in the overall network condition. The flexibility of the system to act on the behalf of either the highway agencies or maintenance contractors with these objectives as follows, as shown in Table 4-10:

Table 4-10: Network-level scenarios description

Scenario #	Name	Description
Scenario 1	Network budget definition	Highway agencies can schematically determine the network budget in the pre-bidding phase
Scenario 2	Sensitivity Analysis	Highway agencies can track the effect of increasing the KPIs' allowable limits on the contractual NLCC
Scenario 3	NLCC Minimization	Maintenance contractors can obtain the optimum M&R action plan to reach a minimal NLCC
Scenario 4	Trade-off Analysis	Maintenance contractor can achieve a better network LOS with a minimal NLCC by applying goal optimization approach

The optimization formulation sheet fits the different scenarios to act as a flexible system, providing different users with the opportunity to choose their own objectives and variables, and place their own constraints, that aid decision makers to achieve their own goals (maximize the NCI and minimize NLCC). As shown in Figure 4-8, the optimization formulation passes through four main stages as follows:

1. Combination stage
2. Formulation stage
3. Optimization stage
4. Tracking stage

The first stage is the combination stage. It is combining all the highways in the network as discussed earlier on the previous section. Each highway characteristics and contractual conditions are defined and combined all together to achieve the total network NLCC and the NCI calculated as follows.

Equation 4-33: Network NLCC calculation

$$NLCC = \sum_z^{l=q} (LCC_{total_z})$$

Equation 4-34: NCI calculation

$$NCI = \sum_z^{l=q} (w_z * HCI_z)$$

Where;

NLCC is the network life cycle costs

z is the number of highways in the network

q is the total number of the highways in the network

w is the weight of each highway in the network

The second stage is the formulation stage. It begins with a constraint formulation, which formulates the constraints check for all the highways (budget and KPIs') and the network constraints (budget and NCI). In addition, it provides the user with a colored cell, either red for not meeting the constraint or green for successful meeting the constraint, which details both the annual network condition status and the network budget status as well. Then, the variable and objective function formulation takes place in the optimization stage.

The third stage is the optimization stage. This is the key stage that links the inputs and outputs. The results of the optimization stage, represented in the network M&R action plan, are the system output. The optimization engine features the MS Excel® Evolver V.5.5 add-in, and uses the GA optimization option. The different optimization scenarios are defined later on this chapter.

Finally, the fourth stage is the tracking stage. An automated sheet was created to summarize the effect of the chosen M&R action plan on the network under study. In addition, it helps the end-user in tracking the results easily and taking corrective actions if necessary.

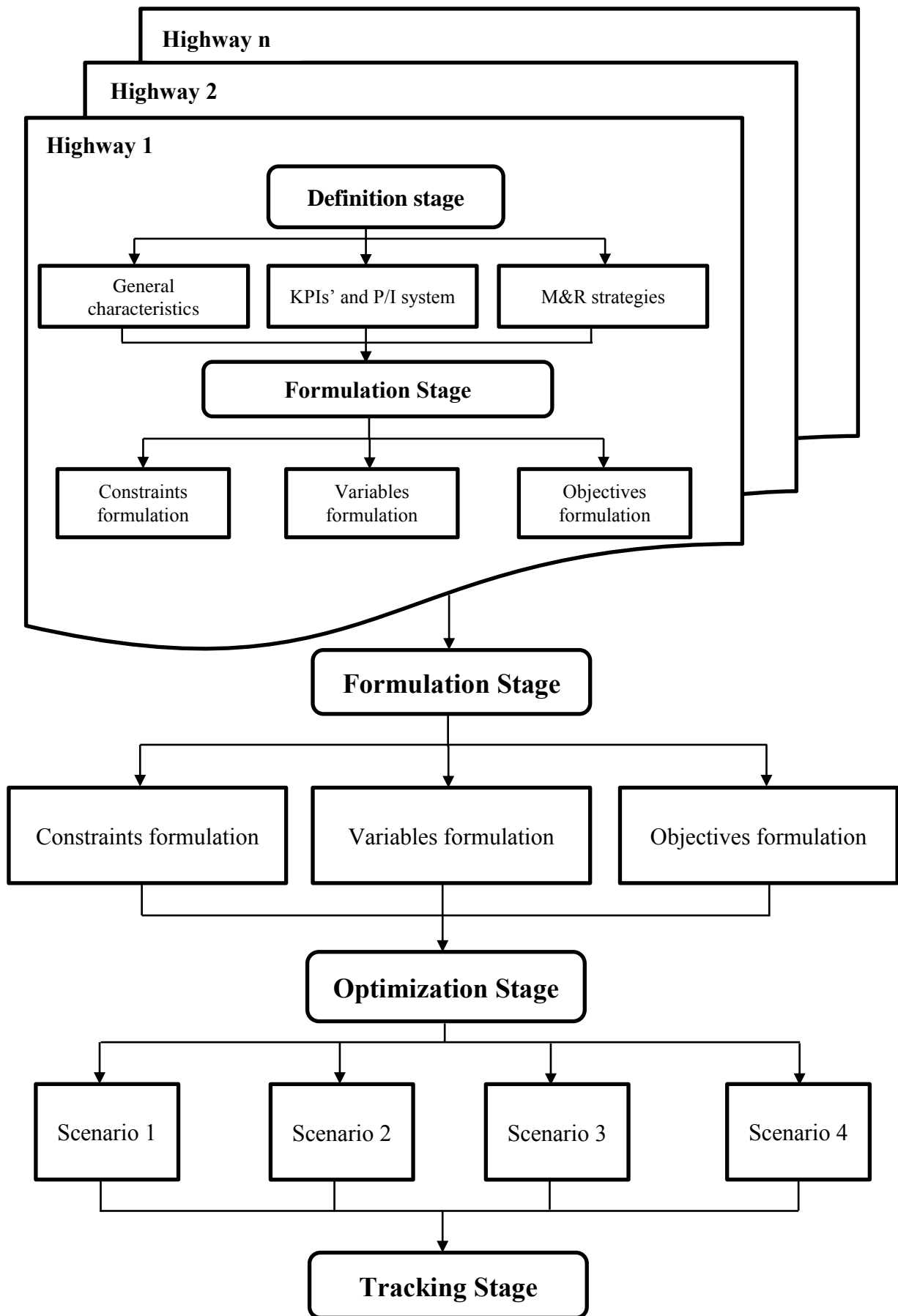


Figure 4-8: Network-level optimization formulation flowchart

4.4.4.1 Scenario 1 - Network Budget Definition

This scenario is mainly for the highway agencies to assign an acceptable budget for the network under study. Table 4-11 shows the main attributes for this scenario.

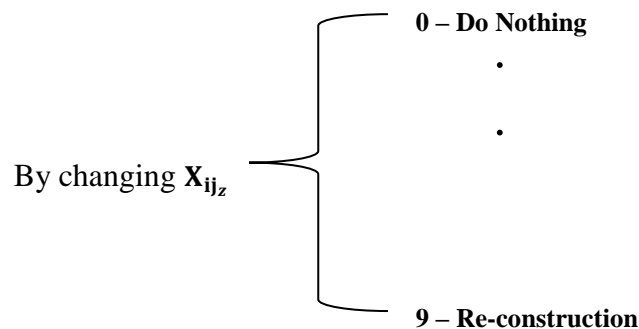
Table 4-11: Scenario 1, 2 and 3 network-level optimization attributes

Attribute	Description
Objective Function	Minimize network LCC <i>Minimize NLCC</i>
Variables	Network M&R action plan - X_{ijz}
Constraints	<ul style="list-style-type: none"> ➤ PCI hard constraint – Highway Constraint ➤ IRI hard constraint – Highway Constraint ➤ Rutting depth hard constraint – Highway Constraint ➤ Surface rating hard constraint – Highway Constraint ➤ Alligator cracking extent hard constraint – Highway Constraint ➤ NCI hard constraint – Network Constraint

As discussed in Table 4-6, the optimization attributes could be mathematically formulated as follows:

Equation 4-35: Objective function

Minimize NLCC



Subject to the following constraints:

Equation 4-36: Annual PCI constraint

$$PCI_{cal_i} < PCI_{LT}$$

Equation 4-37: Overall highway condition index constraint

$$HCI < PCI_{LT}$$

Equation 4-38: Annual Surface rating constraint

$$SR_{cal_i} < SR_{LT}$$

Equation 4-39: Annual IRI constraint

$$IRI_{cal_i} < IRI_{LT}$$

Equation 4-40: Annual Alligator cracking constraint

$$AG_{cal_i} < AG_{LT}$$

Equation 4-41: Annual Alligator cracking constraint

$$NCI < NCI_{LT}$$

Where;

NCI_{LT} is the NCI hard constraint in which the annual and/or the overall NCI resulting from the optimization couldn't exceed

The constraint formulation provides the user with a binary-based coding (0 and 1), which are translated into a colored cell, either red for not meeting the constraint or green for successful meeting the constraint, detailing both the annual status of each highway and the budget status.

4.4.4.2 Scenario 2 – Sensitivity Analysis

This is a sensitivity analysis conducted to give the highway agencies the opportunity to track the direct effect of incrementally increasing the network

highways' KPIs' allowable limits and the P/I system on the KPIs' from one side and on the NLCC from the other side. It also allows the highway agencies to inform the highway users with the budget increase for reaching a better network LOS. The sensitivity analysis will be discussed later on Chapter 5 – Validation and Verification.

4.4.4.3 Scenario 3 – NLCC Minimization

This scenario is mainly for the maintenance contractors to implement the optimum network M&R action plan, taking into consideration the different KPIs' allowable limits and P/I system for each highway in the network, throughout the contract period. The main difference between scenario 3 and scenario 1 is the added constraints for the annual budget and the network budget represented mathematically as follows:

Equation 4-42: Annual budget highway constraint

$$LCC_i < HBT_i$$

Equation 4-43: Annual budget network constraint

$$NLCC_i < NBT_i$$

Where;

NBT_i is the annual network budget constraint. The NPV equations are applicable where; $NBT_n = NBT_1 * (1 + in)^n$

4.4.4.4 Scenario 4 – Trade-off Analysis

This scenario features a goal optimization with an attempt for the maintenance contractor to reach a better M&R action plan with an enhanced NCI and gain higher incentives by then. Table 4-12 shows the main attributes for this scenario.

Table 4-12: Scenario 4 network-level optimization attributes

Attribute	Description
Objective Function	<p>Goal optimization</p> <p><i>Minimize</i> $NDEV_{total} = \left(\frac{NLCC_{total} - NLCC_{limit}}{NLCC_{limit}} + \frac{NCI_{limit} - NCI}{NCI_{limit}} \right)$</p>
Variables	Highway M&R action plan - X_{ijz}
Constraints	<ul style="list-style-type: none"> ➤ Annual budget constraint – Highway Constraint ➤ PCI hard constraint – Highway Constraint ➤ IRI hard constraint – Highway Constraint ➤ Rutting depth hard constraint – Highway Constraint ➤ Surface rating hard constraint – Highway Constraint ➤ Alligator cracking extent hard constraint – Highway Constraint

As discussed in Table 4-12, the optimization attributes could be mathematically formulated as scenario 1 with different objective function as follows:

Equation 4-44: Network-level trade-off objective function

$$\text{Minimize } NDEV_{total} = \left(\frac{NLCC_{total} - NLCC_{limit}}{NLCC_{limit}} + \frac{NCI_{limit} - NCI}{NCI_{limit}} \right)$$

Where;

$NDEV_{total}$ is the total network budget and condition deviation

$NLCC_{limit}$ is the total budget required for the network under study

NCI_{limit} is the minimum allowable network condition index that could be reached even after applying the P/I system

4.5 Summary

Chapter four highlights the research framework in depth. The research framework was demonstrated at the beginning to show the link between the three research disciplines. In addition, the research framework was enhanced by a process flowchart that illustrated the direct relationship between the different modules within each model separately. After that, an integrated framework combining the project-level and the network-level IHAMS was introduced to show the idea behind this integration and the management process for a successful network-level asset management. In addition, a brief idea about the system users and their direct benefits was brought into this study to highlight the importance of the IHAMS for both the highway agencies and the maintenance contractors. Finally, a detailed descriptive section was established for each of the project-level IHAMS and the network-level IHAMS in order to describe the development process for each single module in the system.

5 CHAPTER 5 - VALIDATION AND VERIFICATION

This chapter covers the practical application of the developed project-level IHAMS and network-level IHAMS presented in Chapter 4 – Research Framework. The system was applied on two actual case studies to validate the proposed project-level and network-level IHAMS framework. In addition, it shows a live screenshots from the IHAMS different modules. Then, the decision from the IHAMS and those historical condition data, obtained from GARBLT, are compared with the benefits with respect to both the project-level and network-level. Finally, two scenarios, from each perspective, are presented and their results are analyzed and compared with the actual figures obtained from GARBLT.

5.1 Case Studies

In order to demonstrate and evaluate the applicability of the proposed framework, two hypothetical case studies are undertaken, using the data from GARBLT, as follows:

1. Cairo - Ismailiyah highway - Project-level IHAMS
2. Cairo - Ismailiyah highway, Cairo - Alexandria desert highway, Cairo - Alexandria delta highway, Cairo - Suez highway, and Sokhna highway – Network-level IHAMS

The basic project-level data, which are the pavement characteristics, inspection records, traffic characteristics, PCI, and IRI, are obtained from GARBLT. The KPIs' selected for these case studies were IRI, rutting depth, alligator cracking, surface rating, and PCI as they are the widely used KPIs' for a proper ACR, as per the discussion in Chapter 2 – Literature Review. Other KPIs', such as user costs, potholes, guardrails, barriers, and accidents response time, maintenance safety considerations, and end-user satisfaction, were also theoretically included, as they were not applicable in Egypt, with a minimal allowable acceptable level and P/I system, and the system can be easily extended to include these KPIs'. The KPIs' allowable limits and P/I system were developed based on an extensive literature

review and meetings with GARBLT representatives and maintenance contractors. Furthermore, M&R actions and their associated deterioration rates were developed based on a combination of data obtained from GARBLT and literature review, as presented in Chapter 2 – Literature Review. While, the M&R cost estimates were obtained from several maintenance contractors for the purpose of this study. Finally, an annual inflation rate of 8% was chosen for this study.

5.1.1 Project-level Case Study

This section will discuss the project-level case study and show the results for the different scenarios performed by the IHAMS.

5.1.1.1 Description

The system was applied on an actual case study for a 100 Km-long rural highway in North Eastern Egyptian governorate of Al-Ismailiyah, as shown in Figure 5-1, which is owned and operated by the GARBLT. The total length of the chosen case study was 200 Km, 100 Km for each side (Cairo-Ismailiyah and Ismailiyah-Cairo), as both sides were included in this study. The case study was divided into 4 sections, divided as follows (62 Km, 38 Km, 38 Km, 62 Km), with 35 segments with an increment of 6 Km. The rationale behind choosing this local case study is its unique international dimension. Cairo-Ismailiyah highway is an example of a third-world country horizontal infrastructure connecting between an international waterway (Suez Canal) and a large cosmopolitan consumption center (Greater Cairo).

allowable limits and the P/I system within a certain user pre-defined limits. Moreover, as will be discussed later on in this chapter, a sensitivity analysis was conducted to show the direct effect of increasing the LOS, through increasing the KPIs' thresholds, on the total LCC. This will enable the highway agencies to precisely select the KPIs' allowable limits in order to avoid any extra maintenance cost that will result in a higher LCC.

5.1.1.3 Project-level IHAMS

5.1.1.3.1 Inspection and ACR modules

The inspection and ACR modules are correlated to both the pavement inventory and distresses database through the location code # and distress code # respectively. Firstly, the inspection program begins with choosing the number of samples and the required CI as discussed in Chapter 4 – Research Framework. Then, the system calculates the required number of samples and additional samples in order to prevent extrapolation of unusual conditions across the entire highway. After that, the segments PCI are summed-up to result on the overall highway PCI as shown in Equation 5-1.

Equation 5-1: Actual highway PCI calculation

$$AHCI = \frac{\sum SCI}{\text{Number of inspected segments}}$$

Where;

AHCI is the Highway Condition Index

SCI is the Segment Condition Index

5.1.1.3.2 Future deterioration module

As discussed earlier in Chapter 2 – Literature Review, the deterioration prediction models are classified into deterministic models, represented by regression-based deterioration prediction, and probabilistic models, represented by Markov-based models. In this study, the regression-based deterioration prediction was the one chosen for application on different scenarios and runs. Nevertheless, both of them were applied on the two-main KPIs' (IRI and PCI), for scenario three – LCC minimization, and their results were compared together to analyze the difference between the probabilistic performance prediction and the deterministic performance prediction.

5.1.1.3.2.1 KPI 1 – IRI

Figure 5-2 shows the IRI regression-based deterioration results compared to the Markov-based deterioration results. As shown in Figure 5-2, it was obvious that, in the original case, the difference between the regression-based deterioration and the Markov-based deterioration was not exceeding the 5%. While, the difference between the optimized case results was somewhat different, giving an indication that the regression-based deterioration resulted in a more effective solution, achieving a better IRI.

5.1.1.3.2.2 KPI 2 – PCI

Figure 5-3 shows the PCI regression-based deterioration results compared to the Markov-based deterioration results. As shown in Figure 5-3, it was obvious that, in the original case, the difference between the regression-based deterioration and the Markov-based deterioration was not exceeding the 20%. While, the difference between the optimized results was extremely huge, giving an indication that the regression-based deterioration resulted in a more effective solution, achieving a better HCI.

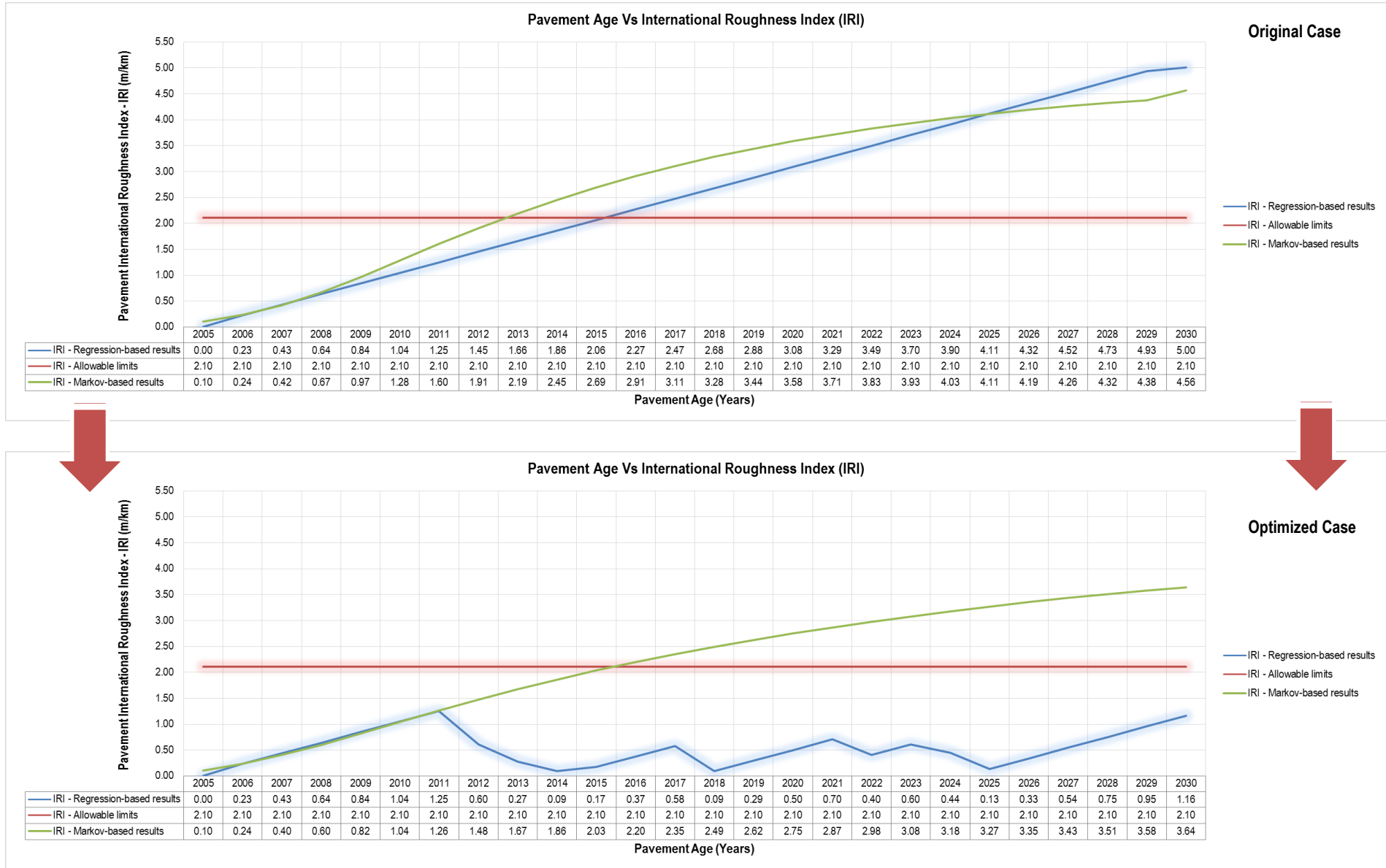


Figure 5-2: IRI comparison between Markov and regression results – Original vs. Optimized case



Figure 5-3: PCI comparison between Markov and regression results – Original vs. Optimized case

5.1.1.3.3 Optimization module (Results and Analysis)

The optimization module is flexible to act on behalf of either the highway agencies or maintenance contractors in different phases, pre-bidding phase and contract-implementation phase. The optimization module, as discussed Chapter 4 – Research Framework, features a GAs’ solution algorithm through the Evolver add-in for Microsoft excel. In this research, the optimization module was applied on five different scenarios. However, two of the objectives will be highlighted in this write-up, as follows:

5.1.1.3.3.1 Scenario 1 – LCC minimization

This scenario is conducted to act as a DSS for the maintenance contractors to minimize the LCC through a pre-defined contractual KPIs’ and P/I system. In this scenario, the objective was to minimize the LCC and maximize the condition. The objective function is to minimize the LCC throughout the contractual period as shown previously in Equation 4-24. The variables are the M&R action plan within the contractual period. While, the constraints are the KPIs’ un-acceptable limits, annual budget limit.

The optimization model features a GAs’ as a solution algorithm through the Evolver add-in. As shown in Figure 5-4, the optimization has been defined for the evolver to begin running with an objective of reaching a minimal LCC throughout the contract period by changing the M&R action plan. After running the optimization engine, the model resulted in a near optimum M&R action plan that minimizes the LCC and meets the KPIs’ unacceptable limits. The M&R action plan could be visualized in Table 5-1. As shown in this table, the M&R action plan seems to be adopting a preventative maintenance plan that extends the service life of the pavement. In addition, Figure 5-5 shows the predicted PCI vs. the actual PCI. It was apparent that a great gap took place at the beginning due to the initial rehabilitation works conducted to return the highway to an acceptable condition. It is represented through a lump-sum amount where; the maintenance contractor should indicate the quantities of measurable outputs that will be executed in order to achieve the

performance standards pre-defined in the contract. This activity is out of the scope of this study.

Finally, the annual costs and the LCC cost are calculated where; the results showed to be effective compared to other several running scenarios, showing a 15.7% savings, compared to the reactive maintenance strategy for a 25-years contractual analysis period, as shown in Figure 5-4 and Table 5-2. Finally, Table 5-2 shows the summary of the scenario outputs, represented in PCI, annual expenditures and total LCC. It shall be noted that the annual budget unacceptable limit has not been reached through the project-level IHAMS with an enhanced highway LOS.

Table 5-1: Scenario 1 - M&R action plan

Year	Decision Variable	Applied Decision Policy
2005	0	Do Nothing
2006	1	Crack Sealing
2007	1	Crack Sealing
2008	6	Patching
2009	3	Micro-surfacing
2010	3	Micro-surfacing
2011	2	Slurry Sealing
2012	1	Crack Sealing
2013	1	Crack Sealing
2014	3	Micro-surfacing
2015	2	Slurry Sealing
2016	1	Crack Sealing
2017	1	Crack Sealing
2018	1	Crack Sealing
2019	1	Crack Sealing
2020	7	Milling and filling
2021	3	Micro-surfacing
2022	6	Patching
2023	1	Crack Sealing
2024	1	Crack Sealing
2025	3	Micro-surfacing
2026	1	Crack Sealing
2027	2	Slurry Sealing
2028	1	Crack Sealing
2029	1	Crack Sealing
2030	1	Crack Sealing

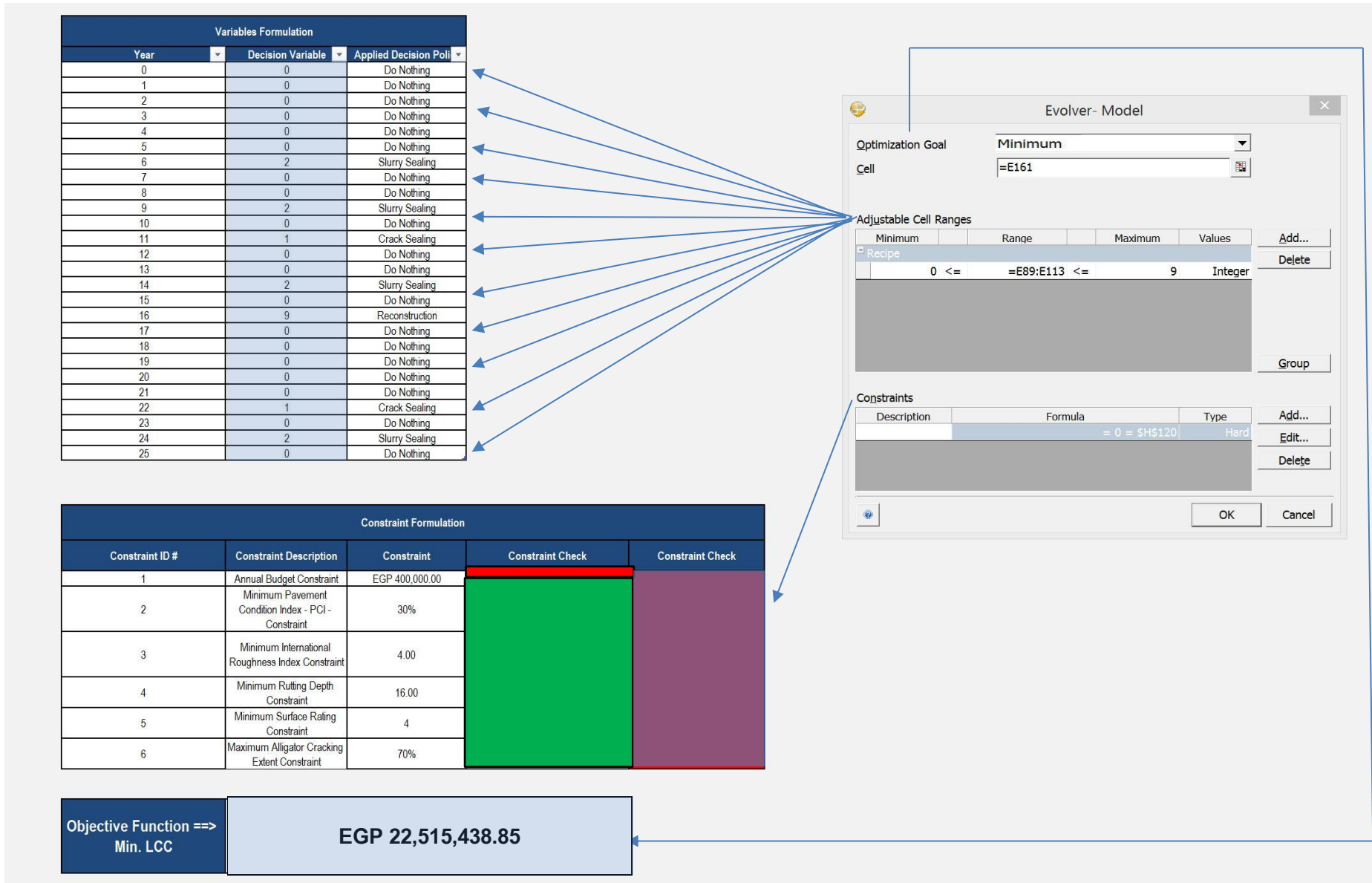


Figure 5-4: Optimization formulation - Minimum highway LCC

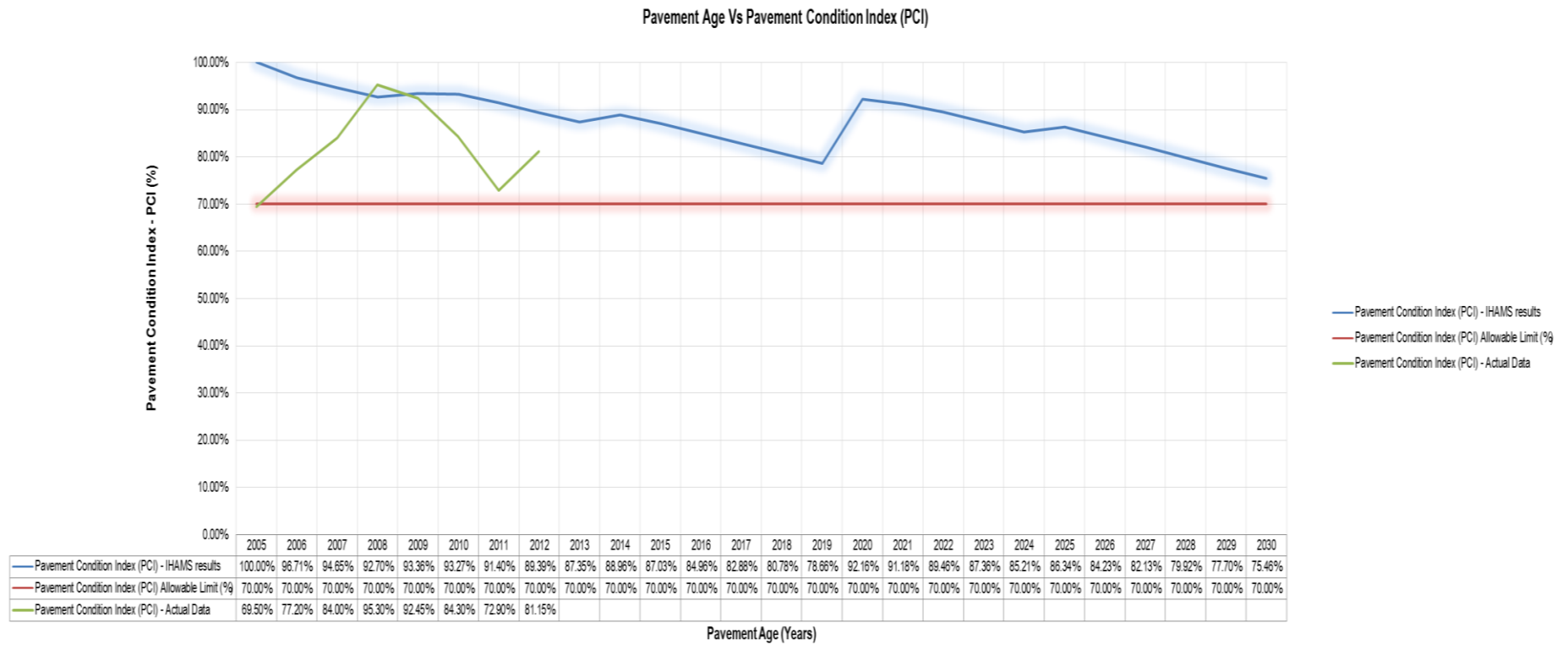


Figure 5-5: Scenario 1 - IHAMS PCI vs. actual PCI

Table 5-2: Scenario 1 – Annual costs and LCC results

Year	PCI	Total Annual Cost (EGP)	Allocated Budget (EGP)
2005	100%	EGP 0.00	EGP 1,400,000.00
2006	97%	EGP 10,800.00	EGP 1,512,000.00
2007	95%	EGP 11,664.00	EGP 1,632,960.00
2008	93%	EGP 1,209,323.52	EGP 1,763,596.80
2009	93%	EGP 1,047,896.21	EGP 1,904,684.54
2010	93%	EGP 1,146,075.90	EGP 2,057,059.31
2011	91%	EGP 25,389.99	EGP 2,221,624.05
2012	89%	EGP 17,138.24	EGP 2,399,353.98
2013	87%	EGP 434.97	EGP 2,591,302.29
2014	89%	EGP 1,559,223.61	EGP 2,798,606.48
2015	87%	EGP 34,542.80	EGP 3,022,495.00
2016	85%	EGP 23,316.39	EGP 3,264,294.60
2017	83%	EGP 591.77	EGP 3,525,438.16
2018	81%	EGP 27,196.24	EGP 3,807,473.22
2019	79%	EGP 29,371.94	EGP 4,112,071.07
2020	92%	EGP 4,187,263.23	EGP 4,441,036.76
2021	91%	EGP 2,638,780.93	EGP 4,796,319.70
2022	89%	EGP 3,552,017.33	EGP 5,180,025.28
2023	87%	EGP 39,960.19	EGP 5,594,427.30
2024	85%	EGP 43,157.01	EGP 6,041,981.48
2025	86%	EGP 3,590,032.33	EGP 6,525,340.00
2026	84%	EGP 50,338.34	EGP 7,047,367.20
2027	82%	EGP 86,984.65	EGP 7,611,156.58
2028	80%	EGP 58,714.64	EGP 8,220,049.10
2029	78%	EGP 1,490.18	EGP 8,877,653.03
2030	75%	EGP 68,484.75	EGP 9,587,865.27
EGP 19,460,189.15			
Objective Function ==> Minimize LCC			

5.1.1.3.3.2 Scenario 2 – Sensitivity analysis

As discussed in the previous scenario, the inputs to the pavement performance modeling are based on data and assumptions, which mean that they are by no means accurate. As discussed in Chapter 1 - Introduction, the risks that the maintenance contractors bears in the PBRMC are usually much more than that of traditional contracts, as being more comprehensive and associated with a P/I system. As a result, performing a series of what-if scenarios would be one of the ways to investigate the financial effect of changing the contractual KPIs' and P/I system. The sensitivity analysis was conducted for three different what-if scenarios as shown in Table 5-3.

Table 5-3: Variables and ranges for sensitivity analysis

Variable	Sensitivity Minimum Range (%)	Sensitivity Maximum Range (%)	Sensitivity Increments
KPIs' Allowable Limits	-30%	30%	10%
Penalites	-30%	30%	10%
Incentives	-30%	30%	10%

5.1.1.3.3.2.1 KPIs' effect on the M&R costs and P/I system

The proposed project-level sensitivity analysis is evaluated for measuring the financial effect, represented by total M&R costs and the applied P/I costs, of the variability in the KPIs' allowable limits. It begins with defining base case KPIs' allowable limits and calculates the new allowable limits for the other six cases, ranging between a -30% and 30% with a 10% increment. Then, the optimization model takes place to solve, considering the new KPIs' allowable limit to obtain the new M&R costs and P/I costs. As shown in Figure 5-7, it was apparent that a 19% savings in the M&R costs was obtained in the 30% KPIs' allowable limits decreasing scenario, reaching a 49% PCI. On the other hand, a 17% jump in the LCC was obvious in the 30% improvement scenario, reaching a 91% PCI. In addition, as shown in Figure 5-6, the penalties decreased by 19% in the 30% KPIs' allowable limit

decreasing scenario. However, they increased by 17% in the 30% improvement scenario. Finally, the incentives increased by 14% in the 30% KPIs' allowable limit decreasing scenario. However, they decreased by 8% in the 30% improvement case. In the case where; PBRMC is funded (fully or partially) from a road toll, this analysis will allow the highway agencies to communicate 1) What service improvements can be attained from increasing a road toll and diverting the revenue to a PBRMC, and 2) What loss in level of service will result if there is a public demand to reduce road tolls.

5.1.1.3.3.2.1 Penalties effect on the PCI and LCC

The proposed project-level sensitivity analysis is evaluated for measuring the financial and condition improvement effect, represented by total LCC and PCI, of the penalties variability. It begins with defining a base case penalties system and calculating the new penalties' values for the other six cases, ranging between a -30% and 30% with a 10% increment. Then, the optimization model takes place to solve, considering the new KPIs' allowable limit to obtain the new LCC and PCI. As shown in Figure 5-8 and Figure 5-9, it was apparent that an 11% savings in the LCC was obtained in the 30% penalties decreasing scenario, reaching a 39% PCI. On the other hand, a 13% jump in the LCC was obvious in the 30% improvement scenario, reaching a 94% PCI.

5.1.1.3.3.2.2 Incentives effect on PCI and LCC

The proposed project-level sensitivity analysis is evaluated for measuring the financial and condition improvement effect, represented by total LCC and PCI, of the incentives variability. It begins with defining a base case incentives system and calculating the new incentives' values for the other six cases, ranging between a -30% and 30% with a 10% increment. Then, the optimization model takes place to solve, considering the new KPIs' allowable limit to obtain the new LCC and PCI. As shown in Figure 5-11 and Figure 5-10, it was apparent that a 9% savings in the LCC was obtained in the 30% incentives decreasing scenario, reaching an 89% PCI. On the other hand, a 12% jump in the LCC was obvious in the 30% improvement scenario, reaching a 62% PCI.

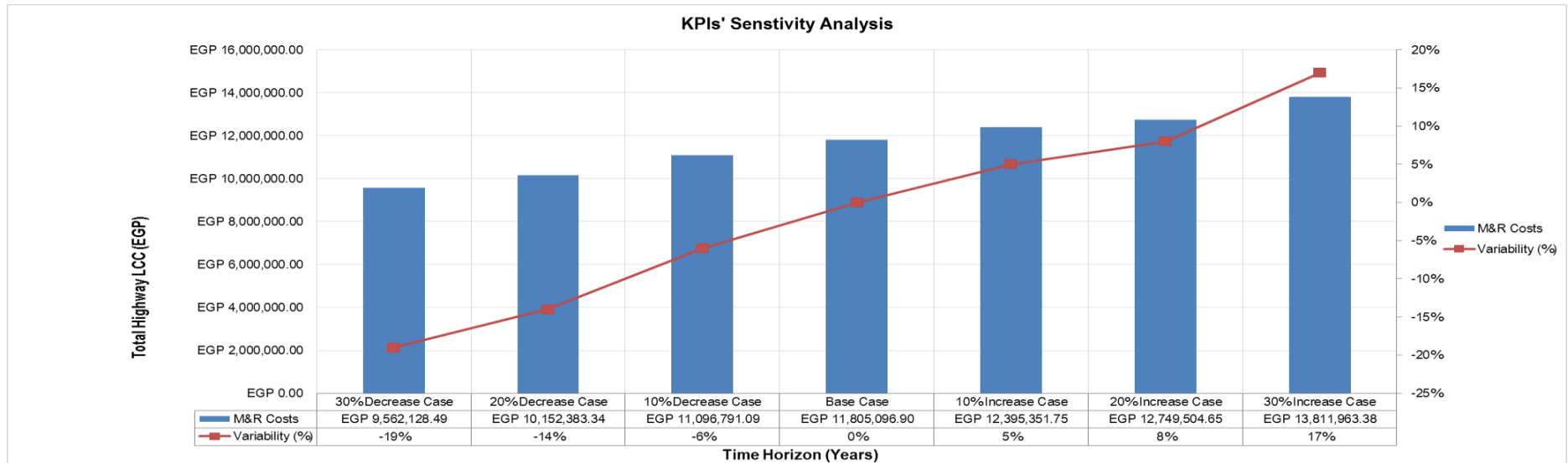


Figure 5-7: KPIs' effect on M&R costs

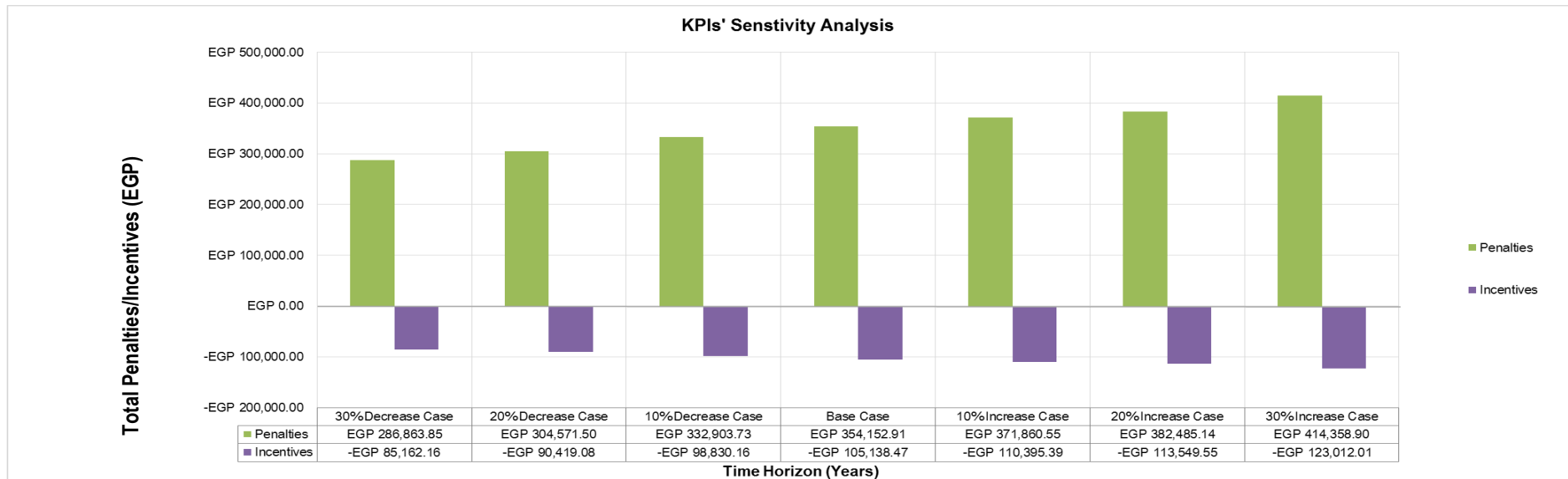


Figure 5-6: KPIs' effect on P/I costs

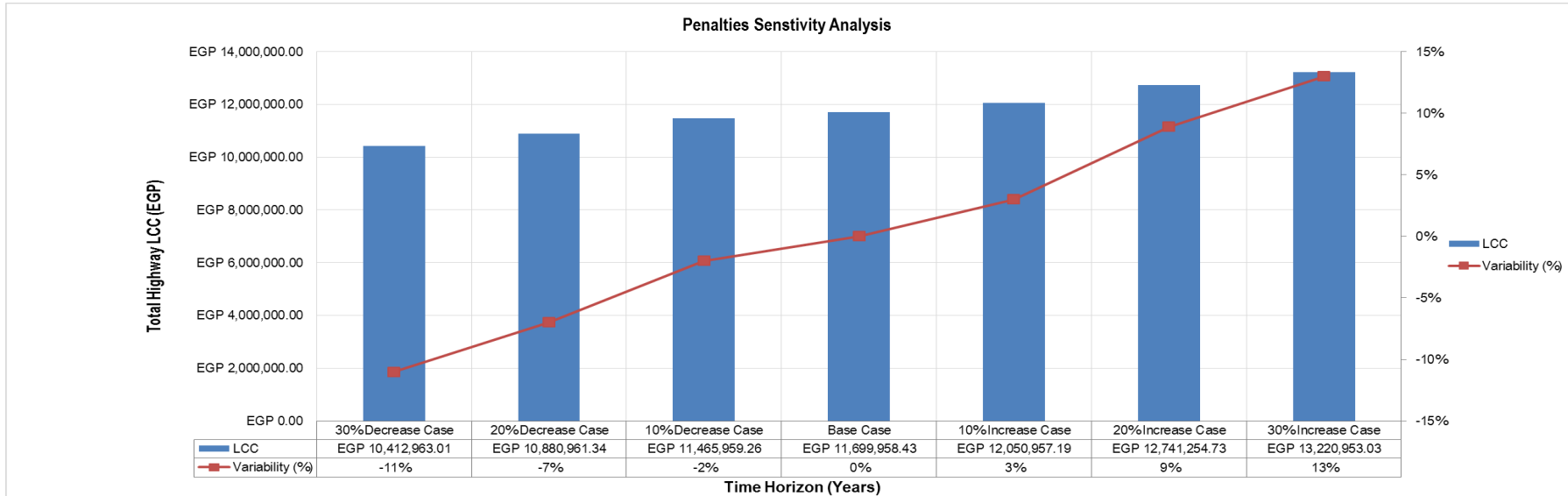


Figure 5-9: Penalties effect on LCC

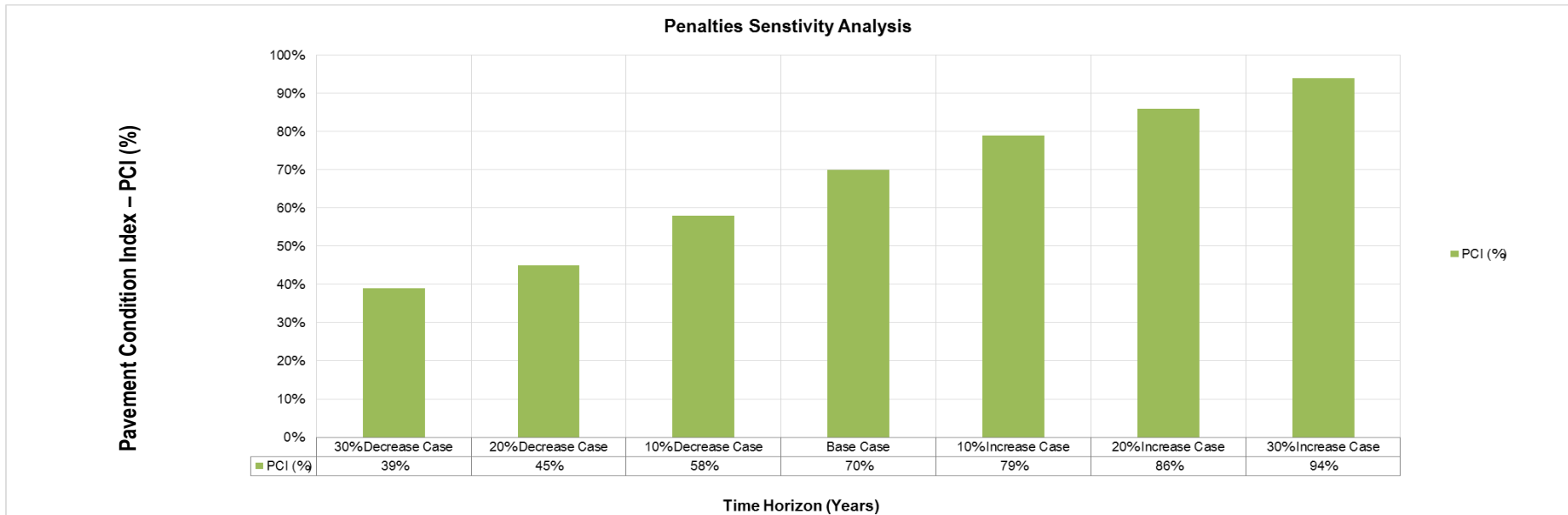


Figure 5-8: Penalties effect on PCI

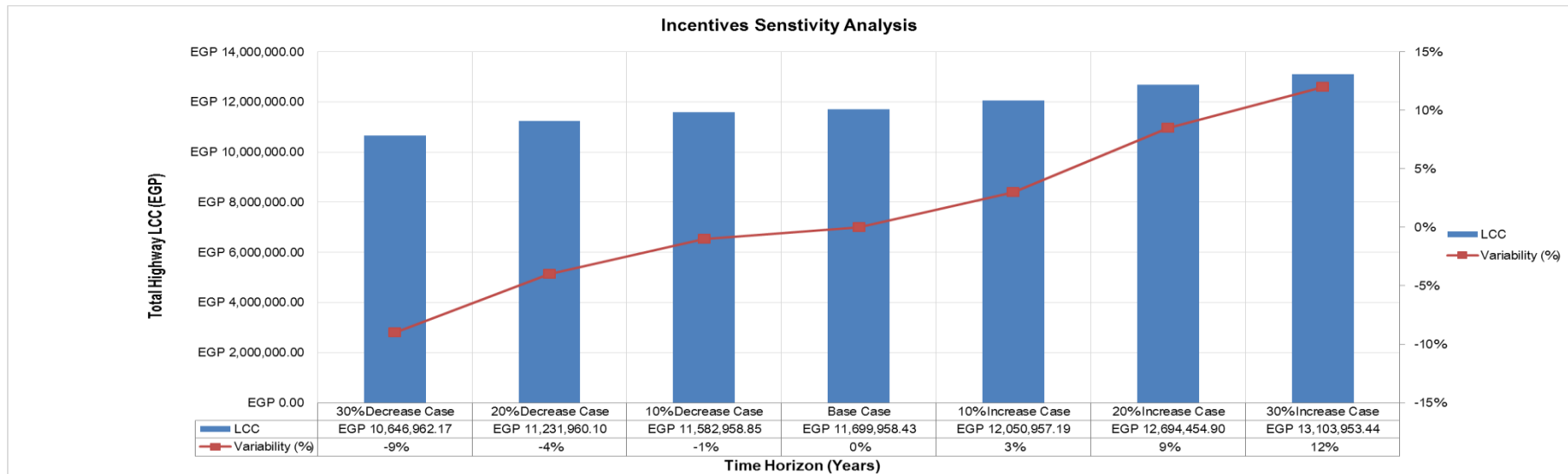


Figure 5-11: Incentives effect on LCC

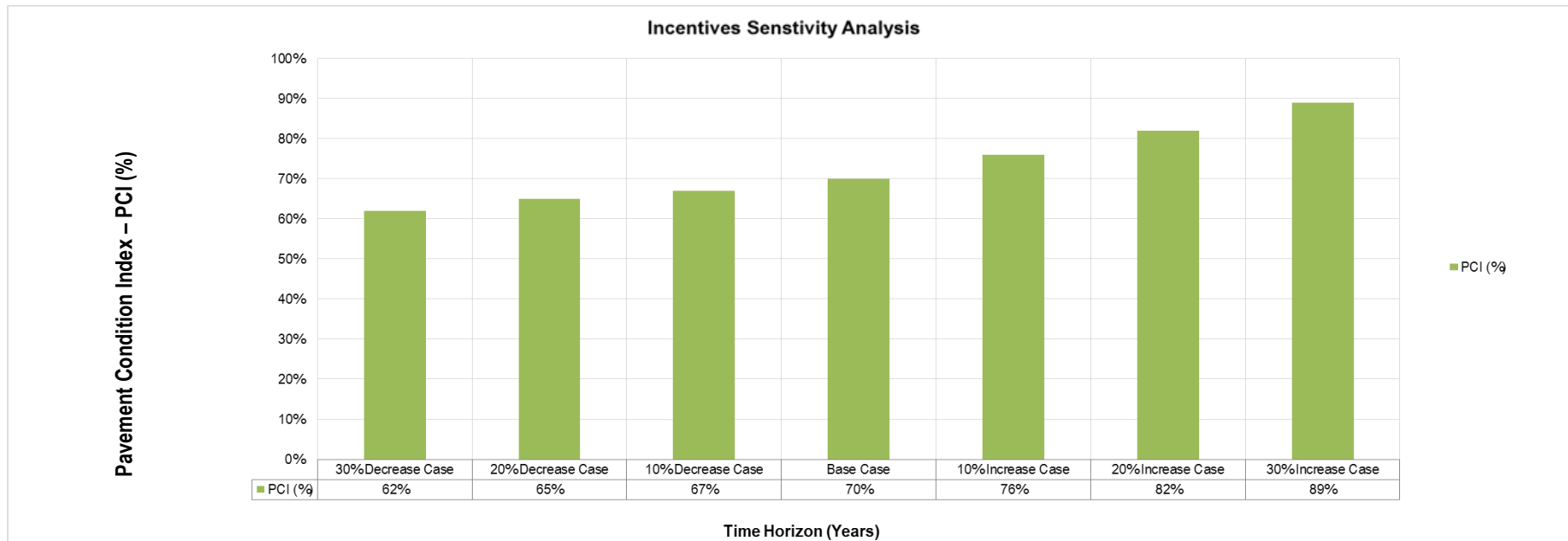


Figure 5-10: Incentives effect on PCI

5.1.1.4 Project-level GIS

The project-level GIS acts as an intelligent spatial database for the segments within the highway. It includes all the segments' records for each pavement with KPIs' future prediction regularly updated from the future deterioration and ACR modules, based on the cut-off date. In addition, it acts as an alert system that notifies both the highway agencies and maintenance contractors with any deviations, either in the KPIs' or in the overall PCI, taking place or going to take place, based on the future deterioration project-level IHAMS results. Finally, it acts as a visualization tool for the highway agencies to track the maintenance contractors' performance throughout the contract period. Figure 5-12 shows a sample from the project-level GIS. As shown in the figure below, each segment is related through the highway ID #, the primary key for the network-level GIS. In addition, the attributes for each segment are defined with pictures showing the severe distress placed in the segment. Finally, in order to alert the end-user, a notifying colored circle that represents the condition state for each segment was developed. As a result, this will enable the highway agencies and/or maintenance contractors to intervene quickly in case of critically unacceptable segments.

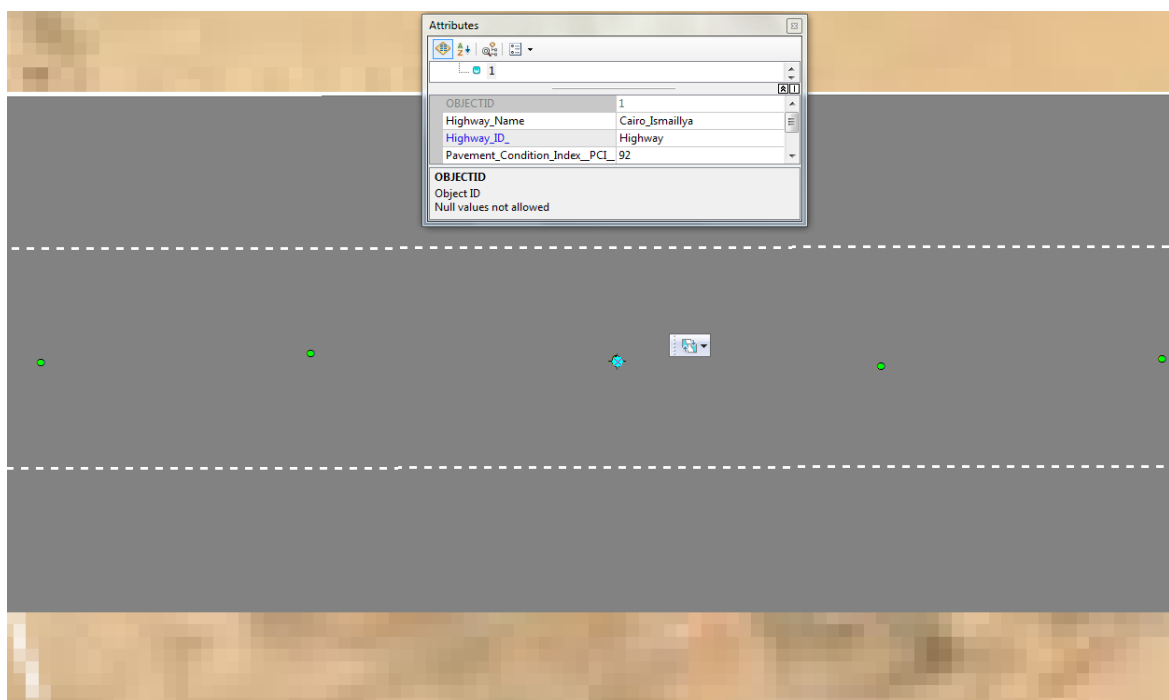


Figure 5-12: Project-level GIS – Sample from a segment in Cairo-Ismailiyah highway

5.1.2 Network-level Case Study

This section will discuss the network-level case study and show the results for the different scenarios performed by the IHAMS. It could be divided into three sub-sections as follows:

5.1.2.1 Description

The system was applied on a case study for a network of highways in Egypt, as shown in Figure 5-13, which is owned and operated by the GARBLT and the Egyptian Army. The network consists of a five long-highways connecting the large cosmopolitan consumption center (Greater Cairo) with other governorates, as follows:

1. Cairo - Ismailiyah highway – 200 Km (Travel and Return)
2. Cairo - Alexandria desert highway – 400 Km (Travel and Return)
3. Cairo - Alexandria agricultural highway – 320 Km (Travel and Return)
4. Cairo - Suez highway – 240 Km (Travel and Return)
5. Sokhna highway – 180 Km (Travel and Return)

Figure 5-14 shows the highway weights distribution in the network. The typical issues in these infrastructure types are the severe budget deficits amounting to poor highway asset management, especially in the network-level management. In the network-level IHAMS, the PBRMC analysis period was chosen to be 25-years. Finally, an annual inflation rate of 8% was applied on the financial calculation of the network-level IHAMS.



Figure 5-13: Highway network-level case study

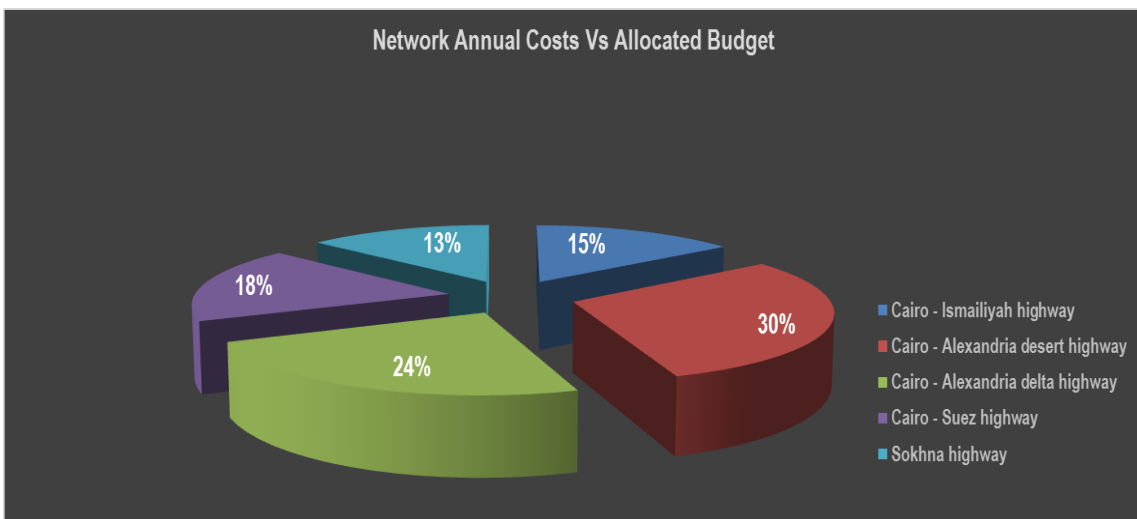


Figure 5-14: Network highway weights distribution

5.1.2.2 Optimization module (Results and Analysis)

The system capability of dealing with five-different highways in the same network, having different KPIs' and P/I system, and different lengths and influence on the NCI as well, is one of the key strengths that differentiates it among other systems. The network-level optimization modules, as discussed Chapter 4 – Research Framework, features a GAs' solution algorithm through the Evolver add-in for Microsoft excel. In this research, the optimization module was conducted for four different scenarios with different objectives. However, two of the objectives will be highlighted in this write-up, as follows:

5.1.2.2.1 Scenario 1 – NLCC Minimization

This scenario is conducted to act as a DSS for the highway agencies that supports their decision for the network allocated budget after selecting the KPIs' and P/I systems for each highway. The allocated budget will give the highway agencies a rough figure about the budget needed to maintain the network and keep the highways KPIs' within the allowable limits, with an objective of minimizing the NLCC. The objective function is to minimize the NLCC throughout the contractual period as shown previously in Equation 4-33. The variables are the highways M&R action plans within the contractual period. While, the constraints are the highways' KPIs' un-acceptable limits, highways' annual budget limit, NCI un-acceptable constraint, and annual network budget limit. The model formulation was discussed previously in Chapter 4 – Research Framework where; all the equations formulating the optimization model for this specific scenario has been highlighted and discussed.

The optimization model features a GAs' as s solution algorithm through the Evolver add-in. As shown in Figure 5-15, the optimization has been defined for the evolver to begin running with an objective of reaching a minimal NLCC throughout the contract period by changing the highways' M&R action plans. After running the optimization engine, the model resulted in a near optimum highways' M&R action plans that minimize the NLCC and meet the highways' KPIs' unacceptable limits. The M&R action plan could be visualized in Table 5-4. As shown in this table, the

M&R action plan seems to be mostly adopting preventative maintenance actions that guarantees a slow-deterioration rate for the highway and by this ensures that the highway will continue its' service life with a proper LOS. As a result, as shown in Figure 5-16, the annual NCI has successfully met the limiting NCI, except for the last year; because of the limited governmental budget assigned for each highway and for the overall network as well.

Finally, the annual costs and the NLCC cost are calculated where; the results showed to be effective compared to other several running scenarios, showing a 10.3% savings, compared to the reactive maintenance strategy for a 25-years contractual analysis period. Table 5-5 shows the summary of the scenario outputs, represented in PCI, annual expenditures and total LCC. It shall be noted that the annual budget unacceptable limit has not been reached through the network-level IHAMS with an enhanced network condition.

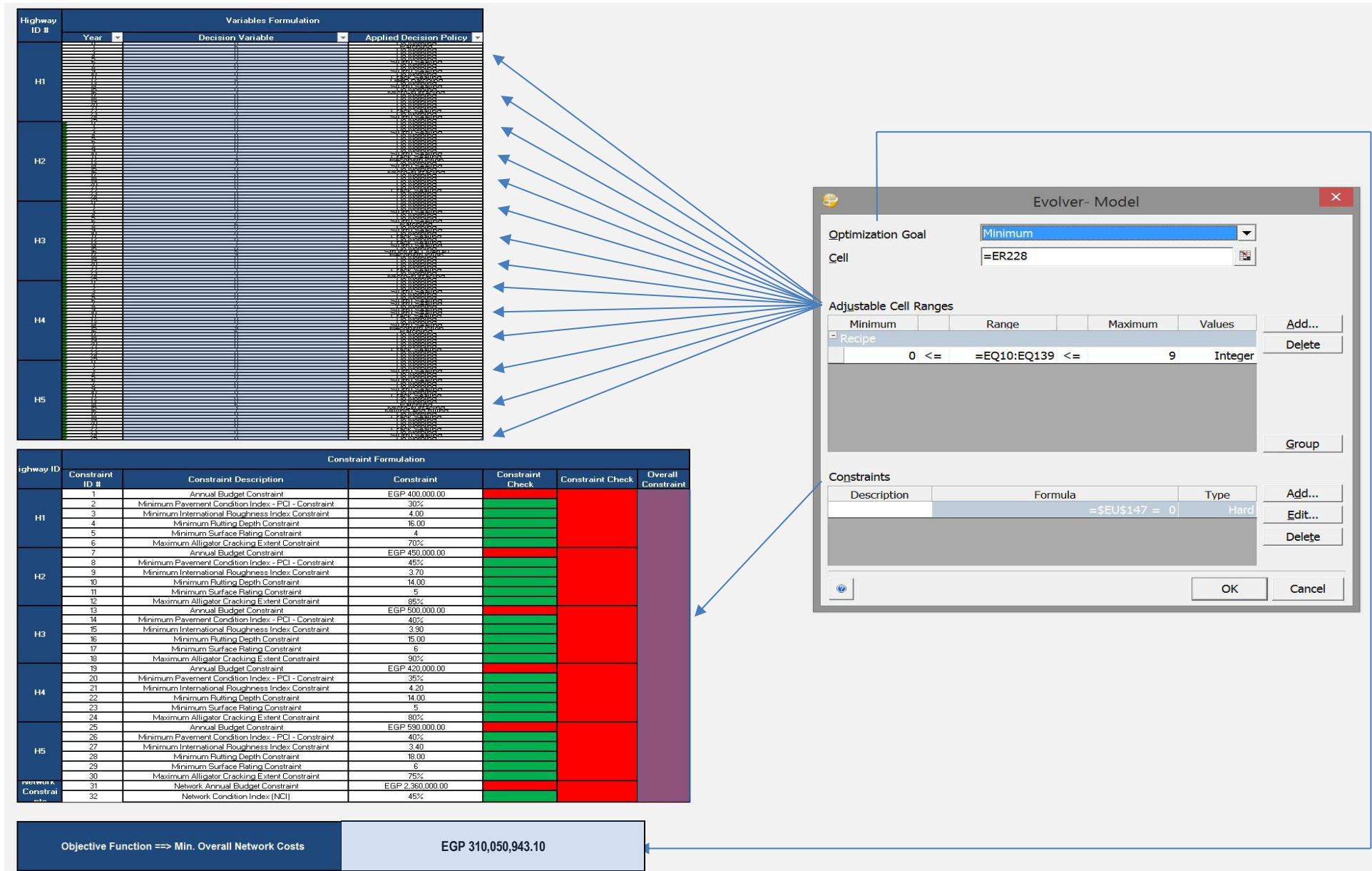


Figure 5-15: Optimization formulation – Minimize NLCC

Table 5-4: Scenario 1 - M&R action plan

Year	Cairo-Ismailliya Highway		Cairo-Alexandria Desert Highway		Cairo-Alexandria Delta Highway		Cairo-Suez Highway		Sokhna Highway	
	Decision Variable	Applied Decision Policy	Decision Variable	Applied Decision Policy	Decision Variable	Applied Decision Policy	Decision Variable	Applied Decision Policy	Decision Variable	Applied Decision Policy
2005	3	Micro-surfacing	0	Do Nothing	0	Do Nothing	0	Do Nothing	0	Do Nothing
2006	0	Do Nothing	3	Micro-surfacing	3	Micro-surfacing	3	Micro-surfacing	3	Micro-surfacing
2007	0	Do Nothing	0	Do Nothing	0	Do Nothing	2	Slurry Sealing	2	Slurry Sealing
2008	0	Do Nothing	0	Do Nothing	0	Do Nothing	0	Do Nothing	1	Crack Sealing
2009	4	Thin Overlay	0	Do Nothing	0	Do Nothing	1	Crack Sealing	2	Slurry Sealing
2010	5	Structural Overlay	5	Structural Overlay	4	Thin Overlay	4	Thin Overlay	4	Thin Overlay
2011	0	Do Nothing	7	Milling and filling	8	Deep patching	8	Deep patching	7	Milling and filling
2012	0	Do Nothing	0	Do Nothing	0	Do Nothing	0	Do Nothing	0	Do Nothing
2013	4	Thin Overlay	1	Crack Sealing	2	Slurry Sealing	2	Slurry Sealing	2	Slurry Sealing
2014	0	Do Nothing	8	Deep patching	3	Micro-surfacing	3	Micro-surfacing	3	Micro-surfacing
2015	1	Crack Sealing	0	Do Nothing	0	Do Nothing	0	Do Nothing	2	Slurry Sealing
2016	8	Deep patching	1	Crack Sealing	7	Milling and filling	3	Micro-surfacing	3	Micro-surfacing
2017	4	Thin Overlay	5	Structural Overlay	2	Slurry Sealing	4	Thin Overlay	4	Thin Overlay
2018	2	Slurry Sealing	3	Micro-surfacing	4	Thin Overlay	2	Slurry Sealing	7	Milling and filling
2019	0	Do Nothing	2	Slurry Sealing	2	Slurry Sealing	2	Slurry Sealing	1	Crack Sealing
2020	5	Structural Overlay	0	Do Nothing	1	Crack Sealing	3	Micro-surfacing	1	Crack Sealing
2021	0	Do Nothing	3	Micro-surfacing	3	Micro-surfacing	3	Micro-surfacing	2	Slurry Sealing
2022	7	Milling and filling	0	Do Nothing	7	Milling and filling	1	Crack Sealing	5	Structural Overlay
2023	0	Do Nothing	5	Structural Overlay	2	Slurry Sealing	2	Slurry Sealing	2	Slurry Sealing
2024	4	Thin Overlay	0	Do Nothing	0	Do Nothing	6	Patching	6	Patching
2025	0	Do Nothing	2	Slurry Sealing	2	Slurry Sealing	2	Slurry Sealing	1	Crack Sealing
2026	3	Micro-surfacing	0	Do Nothing	0	Do Nothing	0	Do Nothing	2	Slurry Sealing
2027	2	Slurry Sealing	4	Thin Overlay	1	Crack Sealing	7	Milling and filling	6	Patching
2028	2	Slurry Sealing	2	Slurry Sealing	2	Slurry Sealing	1	Crack Sealing	2	Slurry Sealing
2029	0	Do Nothing	2	Slurry Sealing	3	Micro-surfacing	2	Slurry Sealing	1	Crack Sealing
2030	0	Do Nothing	0	Do Nothing	4	Thin Overlay	2	Slurry Sealing	3	Micro-surfacing

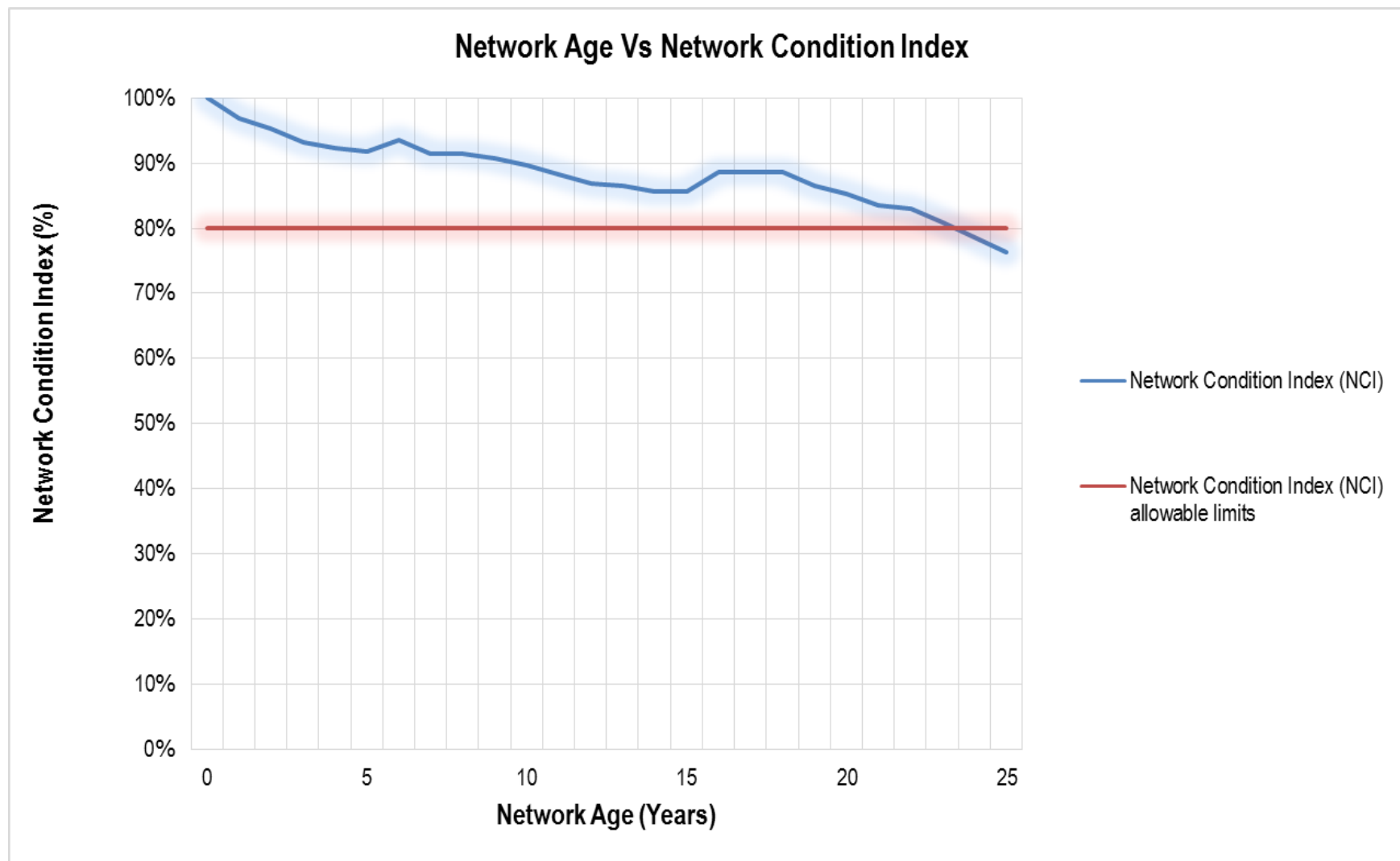


Figure 5-16: Scenario 1 - Network Condition Index IHAMS results

Table 5-5: Scenario 1 – Annual costs and LCC results

Year	Cairo-Ismailliyyah Highway		Cairo-Alexandria Desert Highway		Cairo-Alexandria Delta Highway		Cairo-Suez Highway		Sokhna Highway		Network	
	PCI	Total Annual Costs (EGP)	PCI	Total Annual Costs (EGP)	PCI	Total Annual Costs (EGP)	PCI	Total Annual Costs (EGP)	PCI	Total Annual Costs (EGP)	NCI	Total Network Annual Costs (EGP)
2005	100%	EGP 0.00	100%	EGP 0.00	100%	EGP 0.00	100%	EGP 0.00	100%	EGP 0.00	100%	EGP 0.00
2006	98%	EGP 1,188,000.00	97%	EGP 228,960.00	97%	EGP 231,120.00	97%	EGP 228,960.00	97%	EGP 231,120.00	97%	EGP 2,108,160.00
2007	96%	EGP 233,280.00	95%	EGP 247,276.80	95%	EGP 247,276.80	96%	EGP 1,283,040.00	96%	EGP 1,283,040.00	95%	EGP 3,293,913.60
2008	94%	EGP 267,058.94	93%	EGP 269,578.37	93%	EGP 269,578.37	94%	EGP 269,578.37	94%	EGP 269,578.37	93%	EGP 1,345,372.42
2009	92%	EGP 272,165.82	90%	EGP 253,118.97	93%	EGP 1,477,559.04	95%	EGP 2,212,223.07	92%	EGP 269,444.84	92%	EGP 4,484,511.73
2010	90%	EGP 314,436.21	92%	EGP 1,616,260.88	91%	EGP 311,497.55	93%	EGP 311,497.55	94%	EGP 4,525,530.48	92%	EGP 9,079,222.67
2011	92%	EGP 2,602,473.89	93%	EGP 2,602,473.89	96%	EGP 5,077,997.83	93%	EGP 6,030,122.43	92%	EGP 336,417.36	94%	EGP 16,649,485.40
2012	90%	EGP 342,764.85	91%	EGP 342,764.85	94%	EGP 366,758.39	91%	EGP 342,764.85	90%	EGP 366,758.39	91%	EGP 1,761,811.35
2013	88%	EGP 370,278.59	92%	EGP 5,675,044.57	94%	EGP 3,009,705.07	89%	EGP 366,576.73	91%	EGP 2,010,202.75	91%	EGP 11,431,807.71
2014	90%	EGP 2,198,905.09	90%	EGP 427,786.99	92%	EGP 427,786.99	91%	EGP 2,198,905.09	89%	EGP 427,786.99	91%	EGP 5,681,171.15
2015	88%	EGP 431,785.00	88%	EGP 431,785.00	92%	EGP 2,374,817.50	93%	EGP 3,540,637.00	87%	EGP 462,009.95	90%	EGP 7,241,034.44
2016	86%	EGP 494,307.47	86%	EGP 4,943,074.67	90%	EGP 494,307.47	91%	EGP 494,307.47	90%	EGP 8,860,228.19	88%	EGP 15,286,225.26
2017	84%	EGP 5,323,537.54	84%	EGP 523,905.29	90%	EGP 2,734,858.66	89%	EGP 503,759.93	87%	EGP 498,723.59	87%	EGP 9,584,785.01
2018	82%	EGP 590,158.35	86%	EGP 3,005,184.22	88%	EGP 543,924.75	90%	EGP 2,991,586.10	85%	EGP 581,999.48	86%	EGP 7,712,852.89
2019	80%	EGP 643,245.40	84%	EGP 637,371.02	86%	EGP 622,685.05	94%	EGP 9,399,019.60	83%	EGP 628,559.44	86%	EGP 11,930,880.50
2020	78%	EGP 650,294.67	82%	EGP 650,294.67	93%	EGP 10,150,941.17	92%	EGP 672,499.85	81%	EGP 672,499.85	86%	EGP 12,796,530.21
2021	82%	EGP 3,748,152.55	92%	EGP 10,915,224.56	91%	EGP 678,507.94	92%	EGP 3,720,745.01	79%	EGP 637,396.63	89%	EGP 19,700,026.68
2022	80%	EGP 758,503.70	90%	EGP 740,003.61	89%	EGP 791,803.86	90%	EGP 791,803.86	93%	EGP 11,840,057.78	89%	EGP 14,922,172.82
2023	85%	EGP 12,327,720.15	88%	EGP 855,148.17	91%	EGP 12,307,740.06	88%	EGP 847,156.13	91%	EGP 847,156.13	89%	EGP 27,184,920.65
2024	83%	EGP 884,718.72	86%	EGP 914,928.62	89%	EGP 914,928.62	86%	EGP 914,928.62	89%	EGP 923,560.03	86%	EGP 4,553,064.62
2025	81%	EGP 9,853,496.45	87%	EGP 5,099,320.16	87%	EGP 932,424.48	84%	EGP 9,816,208.79	87%	EGP 932,424.48	85%	EGP 26,633,874.36
2026	79%	EGP 1,031,935.91	84%	EGP 1,031,935.91	84%	EGP 1,092,341.92	81%	EGP 1,031,935.91	88%	EGP 5,537,217.09	83%	EGP 9,725,366.74
2027	77%	EGP 1,190,602.35	86%	EGP 8,943,108.98	82%	EGP 1,114,490.78	79%	EGP 1,179,729.27	89%	EGP 8,915,926.28	83%	EGP 21,343,857.66
2028	75%	EGP 1,274,107.61	84%	EGP 1,285,850.54	80%	EGP 1,285,850.54	77%	EGP 1,285,850.54	87%	EGP 1,244,750.29	81%	EGP 6,376,409.52
2029	73%	EGP 1,306,600.29	82%	EGP 1,306,600.29	78%	EGP 1,306,600.29	75%	EGP 1,319,282.65	84%	EGP 1,230,506.12	79%	EGP 6,469,589.65
2030	71%	EGP 1,499,816.07	80%	EGP 1,486,119.12	75%	EGP 1,499,816.07	72%	EGP 1,486,119.12	82%	EGP 1,486,119.12	76%	EGP 7,457,989.49

Objective Function ==> Minimize Network LCC

EGP 262,755,036.52

Objective Function ==> Maximize Network Condition Index (NCI)

88%

5.1.2.2.2 Scenario 2 – Sensitivity analysis

This scenario is one of the most important aspects that the network-level IHAMS features. As discussed in the previous scenario, the inputs to the pavement performance modeling are based on data and assumptions, which mean that they are by no means accurate. As discussed in Chapter 1 - Introduction, the risks that the maintenance contractors bears in the PBRMC are usually much more than that of traditional contracts, as being more comprehensive and associated with a P/I system. As a result, it was believed that performing a series of what-if scenarios would be one of the ways to investigate the financial effect of changing the NCI.

Therefore, the proposed network-level sensitivity analysis is evaluated for measuring the financial effect, represented by total annual costs (NLCC), of the variability in the NCI. The variables and the ranges studied are presented in Table 5-7. After that, Table 5-6 shows the base case NCI for the other six cases, ranging between a -30% and 30% with a 10% increment. Finally, Figure 5-17 shows the sensitivity analysis. Based on the results, it was apparent that a 25% savings in the NLCC was obtained in the 30% NCI decreasing scenario, reaching a 49% NCI. On the other hand, an 18% jump in the NLCC was obvious in the 30% improvement scenario, reaching a 91% NCI.

Table 5-7: Variables and ranges for sensitivity analysis

Variable	Sensitivity Minimum Range (%)	Sensitivity Maximum Range (%)	Sensitivity Increments
NCI	-30%	30%	10%

Table 5-6: Sensitivity Analysis – NCI and total LCC ranges for different cases

Results Attributes/Scenarios	30% Decrease Case	20% Decrease Case	10% Decrease Case	Base Case	10% Increase Case	20% Increase Case	30% Increase Case
Network Condition Index (NCI %)	49%	56%	63%	70%	77%	84%	91%
Total LCC (EGP)	EGP 96,836,079.26	EGP 114,912,147.38	EGP 123,950,181.45	EGP 129,114,772.34	EGP 136,861,658.68	EGP 143,317,397.30	EGP 152,355,431.36
Variability (%)	-25%	-11%	-4%	0%	6%	11%	18%

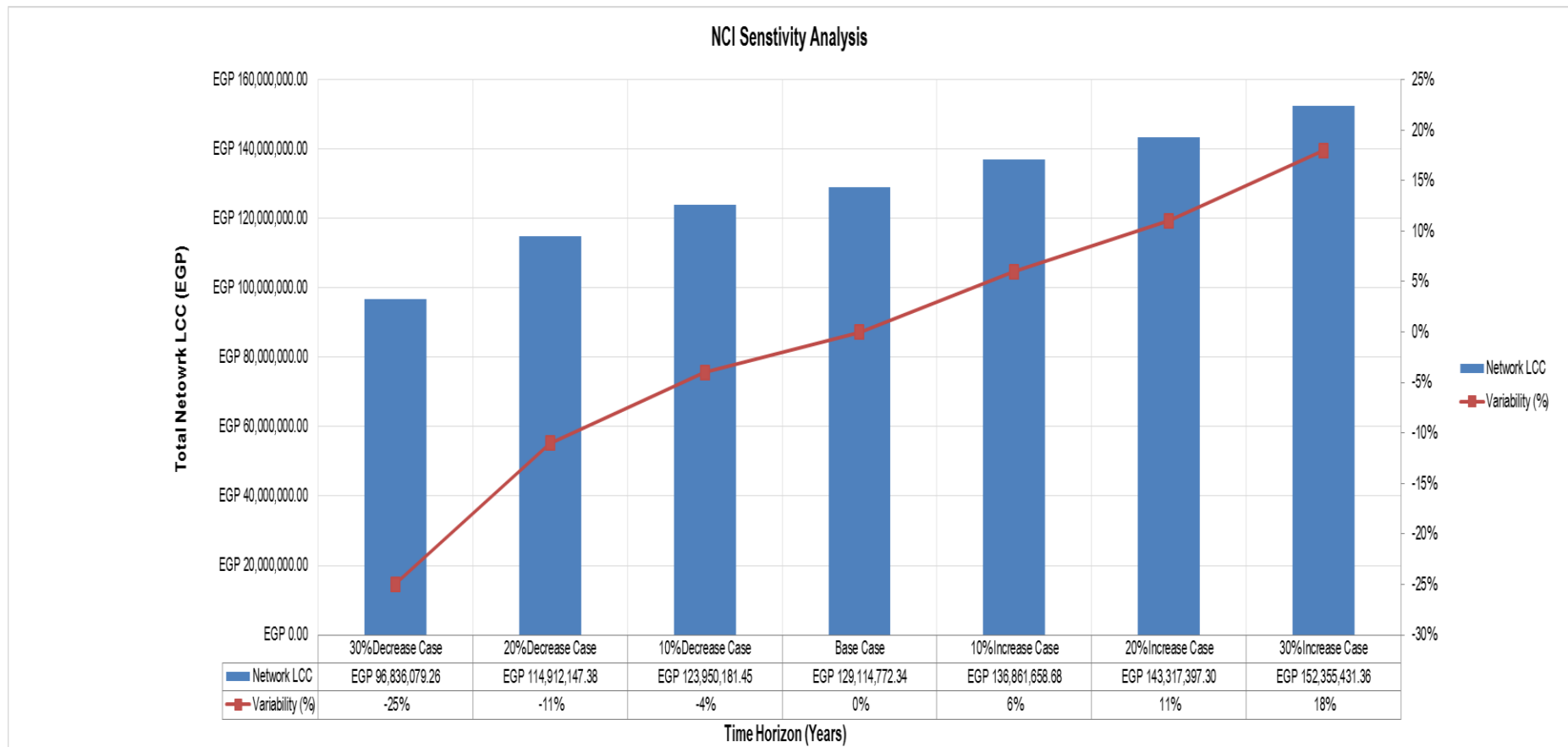


Figure 5-17: NCI sensitivity analysis results

5.1.2.3 Network-level GIS module

The network-level GIS acts as an intelligent spatial database for the entire integrated network highways. It includes all the highways' records including the PCI, highway KPIs' future prediction regularly updated from the future deterioration and ACR modules, based on the cut-off date. In addition, it acts as an alert system that notifies both the highway agencies and maintenance contractors with any deviations, either in the highway PCI or in the overall NCI, taking place or going to take place, based on the future deterioration network-level IHAMS results. Figure 5-18 shows a sample from the developed network-level GIS model. As shown in the figure below, the highway attributes and the network attributes are visualized providing the highway agencies and the maintenance contractors with a visual notification for the actual condition of each highway under the network. This will enable both highway agencies and maintenance contractors to react faster in order to maintain a better and enhanced NCI through an improved highway LOS.

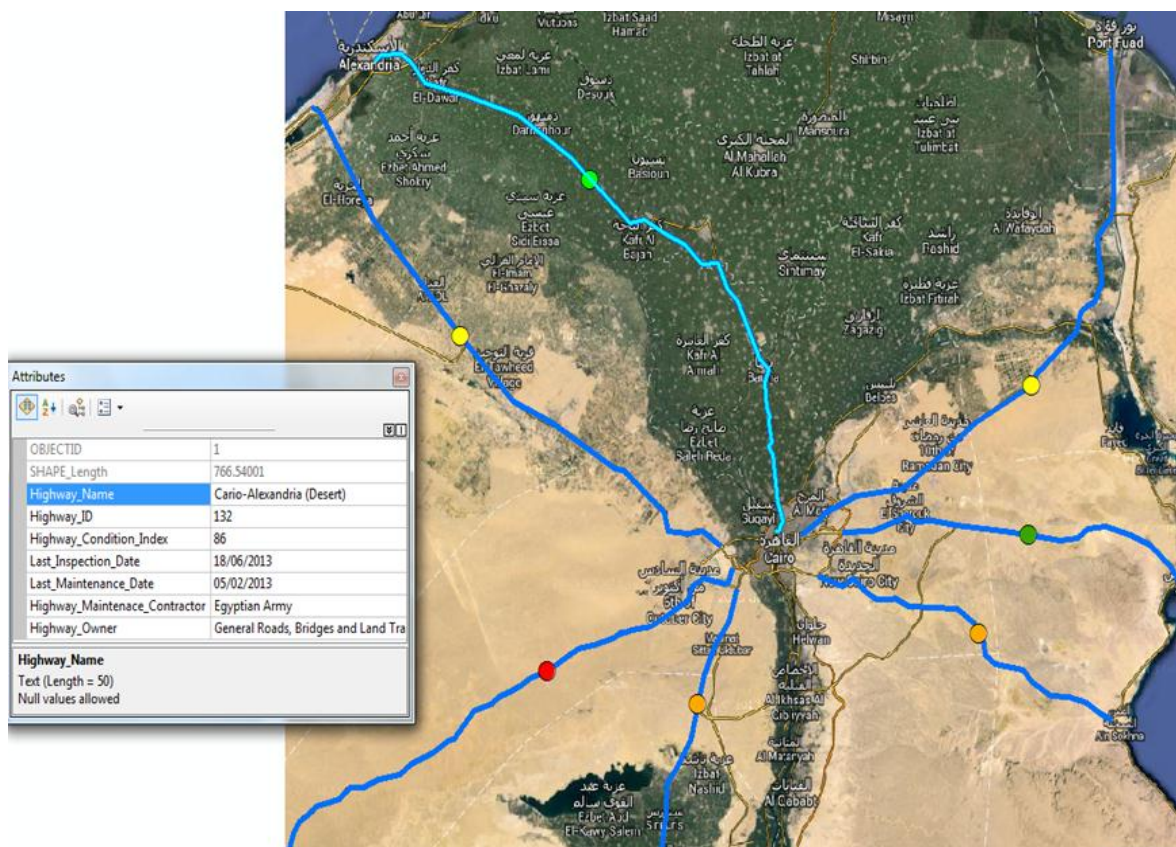


Figure 5-18: Network-level GIS - Sample for Cairo-Alexandria Desert Highway

5.2 Summary

This chapter firstly provided a brief description of the IHAMS software that can be used for both the project-level and network-level for different objectives. In order to validate the IHAMS findings, as well as the optimization model along with the solution algorithm, a project-level real case study was carried out, using the data collected from GARBLT. In addition, another case study was conducted, concerning 5-highways in order to apply the network-level IHAMS, to validate the network-level IHAMS. In the project-level IHAMS, Scenario 4 – LCC minimization - was applied to show the system flexibility in different contracts' phases and to different contractual parties. In addition, a sensitivity analysis was performed with an increment of 10% to show the effect of the KPIs' increase on the LCC. Besides, in the network-level IHAMS, Scenario 3 – NLCC minimization - was applied to show the system capability to work in different phases and aid different users. Finally, a GIS model was developed for both the project-level IHAMS and the network-level IHAMS in order to both visualize the actual and future condition of the highway/network and to act as a decision-making support tool that aids the asset managers in their critical decisions. The IHAMS findings proved to be efficient at both the project-level and the network-level in terms of maximizing the highway/network condition from one side and minimizing the LCC from the other side. In addition, the IHAMS demonstrated its' effectiveness in identifying a proper KPIs' and P/I system, within the pre-bidding stage, that motivates the maintenance contractors to contractually accept the contractual conditions. In conclusions, the IHAMS recommends that the highway agencies should take special care in identifying an appropriate KPIs' allowable limits and P/I system to avoid any extra LCC.

6 CHAPTER 6 - CONCLUSION AND FUTURE RESEARCH RECOMMENDATIONS

This is the last chapter of the write-up, which summarizes the outcomes reached up to this point. It recaps the problem that was proposed and attempted to be solved in this research. Then, it summarizes the main findings of this research and presents the research contributions to the body of knowledge. Finally, it addresses the research limitations and highlight possible directions for future research that are related to the subject matter.

6.1 Research Summary

Highways are major components of the transportation infrastructures. As the highways age, the highway agencies face the pressure of keeping the highway with an acceptable LOS within a very limited M&R funds. As a result, there is a need for a practical and effective solution that guarantees a proper LOS for the highways with a minimal LCC. This contractual solution is represented by the PBRMC where; the highway agencies have to specify certain clearly defined KPIs' to be met or exceeded during the contract period and the payments are explicitly linked to the contractor successfully meeting or exceeding those KPIs', through a contractually defined P/I system.

The main objective of this research is to develop a GIS integrated asset management system for PBRMC. The main rationale behind developing this system is to integrate the PBRMC contractual issues with the PMS in the two phases; pre-bidding phase and contract-implementation phase. The pre-bidding phase is applicable before the bidding stage to allow the highway agencies and the maintenance contractors to predict the LCC, under the pre-defined KPIs' and P/I system, throughout the contract period. On the other side, the contract-implementation phase is applicable after the contract is awarded. It will aid the maintenance contractor to control the expenditures and reach an enhanced condition for the highway under

study. The proposed framework is innovative and flexible in its' power to serve both the highway agencies and maintenance contractors to optimize and reach their goals.

6.2 Research Findings

Apart from the contributions that the developed framework has made to the body of knowledge, there are some newly developed concepts that can be regarded as specific findings of this research, which can be utilized in implementing a proper highway asset management under the PBRMC. These finding could be listed and briefly discussed as follows:

1. The developed framework incorporates a deterministic regression-based deterioration model that predicts the future condition of the highway and the effect of applying different M&R strategies on each KPI solely and on the highway/network condition under the PBRMC contractual obligations (KPIs' allowable limits and P/I system).
2. LCC optimization proved to be a complex task, particularly in the case of huge highway networks. Nevertheless, the developed framework successfully satisfied its' purpose of managing the LCC under PBRMC.
3. Development a practical system that integrates the PBRMC and PMS is the best way of handling the problem of highway/network budget allocation and KPIs' and P/I system determination.
4. Future deterioration is well-known to be a multi-faceted phenomenon characterized by an array of variables associated with it. Therefore, due to the inherited complexity of the outcome, it is recommended to account for all possible variables pertaining to pavement deterioration due to its' uncertainty.
5. Sensitivity analysis of different KPIs' limits showed to be beneficial for highway agencies to calculate the budget variance in different cases and carefully decide if it is worth to improve the LOS, through improving the KPIs' allowable limits, or not. The budget variance results due to the high influence of the LOS and M&R action plan choice.

6. Effect of each maintenance strategy is localized only on the KPIs' that are improved due to its' application, as discussed in Chapter 4 – Research Framework.
7. The IHAMS flexibility to fit different users, which are represented by the highway agencies and the maintenance contractors, and different phases, beginning with the pre-bidding phase and ending-up with the contract-implementation phase, is a strength point that differentiates the IHAMS from other developed systems.
8. The integration between the project-level IHAMS and the network-level IHAMS, as discussed in Chapter 4 – Research Framework, facilitates the use of the system by highway agencies to allocate the highway/network budget with a high level of precision. In addition, it improves the management approach for highway networks as the output of the project-level IHAMS is directly linked to act as an input in the network-level IHAMS to aid the asset managers in their decision-making process.
9. The IHAMS results proved that the system is very responsive to slight changes in the KPIs' allowable limits and P/I system. Any deviation from the KPIs' allowable limit will be transmitted to a penalty that will be directly applied on the IHAMS financial module due to that deviation. Therefore, unnecessary tighter KPIs' allowable limits, which do not add much value to the overall highway LOS, should be avoided by the highway agencies in the PBRMC.

6.3 Contributions to Body of Knowledge

The scope of this research, as clearly stated in section 1.4 - Research Scope and Objectives, is to develop a fully integrated Highway Asset Management System (IHAMS), which combines the aspects of a project-level and network-level PMS with a GIS system from one angle and PBRMC through the KPIs' from the other angle. The research is aspiring to, at least, aid both the highway agencies in the KPIs' and P/I system identification in the pre-bidding stage, and the maintenance contractors to create a near optimum M&R action plan for meeting the KPIs' and minimizing the

LCC. Based on the current developments, this research has proposed several contributions as follows:

- 1. Better understanding of the highway management needs:** This study has extensively reviewed the recent research and practices carried out on the components of the PMS. This knowledge was obtained from previous research conducted on different countries and interviews with highway agencies representatives and maintenance contractors.
- 2. Integration of PMS and PBRMC:** This main idea behind this research was developing an integrated PMS under the umbrella of PBRMC. This study discussed in depth the essence of integrating the PBRMC and the PMS to guarantee a proper highway asset management under the PBRMC.
- 3. Integration of project-level IHAMS and network-level IHAMS:** One of the advantages of this research is the integration between project-level and network-level IHAMS. Network-level is a highly complex and complicated task if it is taken in its totality. As a result, the integration between the project-level and the network-level was made in two-sequential optimization cycles. The first one was for the project-level IHAMS to get a rough figure for the needed budget, given a pre-defined contractual KPIs' and P/I system. The second one was for the network-level IHAMS to result in the network M&R action plan for all the highways in the network. This methodology has proved to provide a valuable outcome from both the project-level and network-level.
- 4. Comparison between deterministic (Regression-based) and probabilistic (Markov-based) future deterioration models:** Deterioration modeling is an integral part of infrastructure asset management, predicting the future condition and planning the maintenance and rehabilitation treatments. This study compared both the regression-based deterioration model with the Markov-based deterioration model to calculate the efficiency of the probabilistic models compared to the deterministic ones.

- 5. Efficient handling of large-scale problems through different optimization algorithms:** This research has investigated different optimization techniques and solution algorithms for handling such a typical infrastructure asset management problem, represented in the large-scale highway networks. It was obvious that many optimization algorithms were inapplicable to this complex problem, as the optimization performance depend on the objective function, problem size (number of variables), and the problem formulation. It was concluded that, for the network-level IHAMS, it is better to prioritize the highways based on the necessity and importance of each highway on the overall network. This facilitates the decision-making support tool to reach the optimum M&R action plan in a less time.
- 6. System Flexibility:** The flexibility and applicability of the system for different users is one of the main contributions that IHAMS reached in both the project-level and network-level. Both highway agencies and maintenance contractors could use the IHAMS in the pre-bidding stage and the contract-implementation phase. The main applications for IHAMS could be summarized as follows:
- a. Highway/Network budget definition: This has been always a headache for highway agencies to allocate the budge for a certain highway/network to guarantee a proper condition. Therefore, this research developed both a project-level and a network-level IHAMS that aids decision-makers in highway agencies to allocate the highway/network budget without substantially investing time and resources to conduct this task.
 - b. What-if Scenarios could be easily performed on a simple and automated manner.
 - c. 25-year planning horizon forecast for the condition and M&R action plans.
 - d. Accounts for the importance of a certain highway to the network through the prioritization stage.

6.4 Concluding Remarks

At the closing stages of this write-up, the following points could be concluded:

1. There is a gradual switch from method-based, material-based, and method and material-properties based contracts to PBRMC for highway maintenance. Unlike the typical cost estimation process in method-based contracts where; the cost is based on the quantity of work performed regardless the performance, the cost estimation of PBRMC requires relating cost to performance through defined SMART KPIs' and P/I system.
2. The current highway asset management for Egyptian highway is traditional and is not capable of helping in the decision-making process for enhancing a proper LOS to match the end-user expectations. There is a strong need for both a project-level and network-level IHAMS to increase the expenditures efficiency and improve the highway/network condition.
3. GIS is a good referencing method to present the highway/network as it generates the spatial maps for highway networks in terms of the classification and condition, facilitating the asset managers to track the network performance and take corrective M&R actions to improve the performance and meet the end-users expectations.
4. GIS can be used as an internal monitoring tool for the highway agencies to evaluate the performance of the on-site inspectors and provide them with adequate trainings, whenever needed.
5. User-friendly system facilitates the implementation of the system for both highway agencies and maintenance contractors to reach their objectives in an easy and fast manner, without the need for extensive training on the system.

6.5 Research Limitations

Despite the capabilities and flexibility of IHAMS, it has some limitations that could be summarized as follows:

1. Due to the limited available condition data, the IHAMS studied five KPIs' as discussed in Chapter 4 – Research Framework. The system could be improved by including a future predication model for all the KPIs' to be able to precisely predict the future performance of each KPI and properly apply the P/I system.
2. Due to the lack of available data, The IHAMS did not study the user costs, which is believed to be a critical item that should be considered in the LCC calculations.
3. The GIS was developed for the purpose of spatial and condition visualization from one side and internal monitoring tool for the highway agencies from the other side. However, it has not been extensively used as a main database tool to include all the highway and segments attributes.
4. The IHAMS in its' current format considers eight M&R strategies with their associated unit costs. A more precise cost model for each distress type could be developed through surveys of maintenance contractors and highway agencies involved in the highway maintenance.
5. The after-repair deterioration is assumed to follow the same pattern as the before-repair deterioration. However, in practice, the after repair deterioration rate is much faster than that assumed. Therefore, more research is needed to estimate the after-repair behavior for each KPI.
6. The regression-based deterioration model used in the development of the IHAMS is based on several literature review and actual data obtained from GARBLT, which varies from one location to another due to the environmental conditions, etc... Therefore, accurate deterioration models for each location should be developed based on the regular inspection reports conducted by the highway agencies. After that, the application of these deterioration models will be easy following the same framework as discussed in details in Chapter 4 – Research Framework.

7. The project-level and network-level M&R action plans were compared to the M&R action plans that were actually implemented by the GARBLT. However, it is worth to examine them against different highways to guarantee its' applicability.
8. The PBRMC initial rehabilitation works activity is not included in the IHAMS calculations.
9. The existing system deals with an entire highway as one lump in the decision making process. For example; when we decide to do a micro-surfacing strategy in 2014, it is applied on the full entire highway, which may be impractical due to the inability to mobilize enough construction resources in one year and makes it impossible to disrupt the entire highway through this activity.
10. The number of working resources for the different M&R strategies should be taken into consideration to account for the traffic congestions.
11. The placement of a resource constraint, in the M&R strategies scheduling plan, that constitutes for the available number of resources with the maintenance contractor throughout the contract period.

6.6 Directions for Future Research

This section lists and goes through some possible directions for future research, which can be conducted to follow-up with the research presented in this thesis. These directions could be summarized as follows:

1. The wider application of the same framework to accommodate for other KPIs', through placing weights that constitute for the importance of each KPI, in order to guarantee a more accurate and precise LCC calculation.
2. The application of a user-cost model to be able to track the effect of the improved LOS, through an enhanced condition, on the user costs.
3. Further work should be done to explore additional uses of the GIS within the IHAMS framework. There could be in-house software within the GIS to run for an optimum M&R action enabling the user to use only the GIS model to spatially visualize the output on the GIS system.

4. Development of a more precise cost model for each distress type, based on actual surveys of maintenance contractors and highway agencies involved in the highway maintenance.
5. Accurate estimation of the after-repair behavior for each KPI is needed as it is not always the same as its' before-repair behavior.
6. Accurate deterioration models for each location should be developed based on the regular inspection reports conducted by the highway agencies.
7. Comparison between the optimization algorithms is needed to be aware of each algorithm applicability. In addition, a list of advantages, disadvantages, pricing, and the inputs required from a highway agency to be able to adapt the software should be also discovered.
8. A visual basic program in combination with the Microsoft-excel can be employed in the future to ease the system implementation for end-users.
9. The IHAMS assumes that the deterioration and condition improvement are deterministic; however, it is important to incorporate uncertainty and probabilistic approach in the development of the IHAMS components.
10. The initial rehabilitation works activity, which is essential to return the highway under the contract to an acceptable condition as per the contractual KPIs', could be included in the PBRMC cost calculations.
11. Use the GIS to conduct an inspection analysis, which enables the highway agencies to provide their on-site inspectors with proper trainings to increase their confidence on the maintenance contractors' performance.
12. Integrate the network data through spatial technologies that links both the geographic data with the geometric and tabular data for the highways within the network.
13. Add the resource plan to the IHAMS, to account for both the traffic congestion and the limited available resources with the maintenance contractor, within the PBRMC contract period.

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8 APPENDICIES

8.1 APPENDIX A – PAVEMENT INVENTORY DESCRIPTION

8.1.1 Location Identity

The location identity sub-module consists of all the information necessary to define the location identity of the highway. Appendix table 8-1 shows the information about the location identity, which includes the following attributes:

Appendix table 8-1: Location Identity Attributes

Attribute Name	Description	Type/Domain
Country name	It states the country name of which the highway is located.	Text
Road type	It states the road type for the intended road under study.	Look-up values (Province roads, Region roads, District roads, State roads, Interstate roads)
Qualifier	It describes a roadway, which shares the same route number and serves some specialized purpose.	Look-up values (Qualifier, No Qualifier)
Residence city name	It states the residence city name.	Text
Destination city name	It states the destination city name.	Text
Highway number	It states the highway number.	Numeric
Highway owner agency	It states the highway owner agency.	Text

Highway inspection agency	It states the highway inspection agency.	Text
Highway maintenance agency	It states the highway maintenance agency.	Text
Segment ID #	It is a unique ID # assigned for each segment.	Code
Segment length (m)	It states the exact length of each segment.	Numeric
Entry Date	It states the date of this entry.	Date

In this sub-module, unique location ID # is automatically generated to create a unique number for each segment. This is a sample for the location ID # “EGYPRO01QAH40ISM01010010001”. The previous unique ID # was automatically generated based on the following criteria:

1. “**EGY**” represents the country name.
2. “**PR**” represents the route type.
3. “**001**” represents the qualifier code.
4. “**QAH**” represents the residence city name.
5. “**40**” represents the state highway number.
6. “**ISM**” represents the destination city name.
7. “**01**” represents the sector ID #.
8. “**001**” represents the section ID #.
9. “**0001**” represents the segment ID #.

8.1.2 Physical Characteristics

The physical characteristics sub-module consists of all the information necessary to define the physical characteristics of the highway. Appendix table 8-2 shows the information about the physical characteristics, which includes the following attributes:

Appendix table 8-2: Physical Characteristics Attributes

Attribute Name	Description	Type/Domain
Total number of lanes	It represents the total number of lanes.	Numeric
Number of road ways	It represents the number of roadways. It could be either divided or un-divided.	Look-up values (Divided, un-divided)
Pavement shoulder width (m)	It represents the pavement shoulder width.	Numeric
Pavement width (m)	It represents the total width in feet of all travel lanes in both directions and including turning and acceleration/deceleration lanes, but not including paved shoulder width or medians.	Numeric
Pavement type	It states the pavement type.	Look-up values (Unpaved, Overlay, Brick or Block, Asphalt, Concrete)
Pavement layer type	It states the pavement layer type.	Text

Pavement layer thickness (mm)	It represents the pavement layer thickness.	Numeric
Performance Grade binder (PG) type	It states the PG binder type.	Look-up values (PG 58-34, PG 64-22, PG 64-28, PG 70-22, PG 76-22, PG 82-22)
Base layer type	It states the base layer type.	Text
Sub-base layer type	It states the sub-base layer type.	Text
Functional class	It represents the functional characteristics of the highway.	Look-up values (Urban, Rural)
Terrain type	It represents the terrain type.	Look-up values (Flat, rolling, hilly)
Access control	It represents the access control for the highway	Look-up values (full access, partial access, no access)
Entry date	It represents the date of the entry.	Date

8.1.3 Traffic Characteristics

The traffic characteristics sub-module consists of all the information necessary to define the traffic characteristics of the highway. Appendix table 8-3 shows the information about the traffic characteristics, which includes the following attributes:

Appendix table 8-3: Traffic Characteristics attributes

Attribute Name	Description	Type/ Domain
Annual Average Daily Traffic (AADT)	It represents the traffic volumes are calculated from sample counts taken in the field, or upon estimates or projections by the highway agency.	Numeric
Percentage of Trucks (%)	It represents an average percentage of the trucks.	Numeric
Volume/Capacity Ratio (V/C Ratio)	It is the one-way design hour volume for a road segment divided by the one-way adjusted rated capacity of the road segment.	Numeric
Entry date	It represents the date of the entry.	Date

8.1.4 Historical Inspection and Condition Rating

The historical inspection and condition-rating sub-module consists of all the information necessary to define the inspection and condition ratings of the highway. Appendix table 8-4 shows the information about the historical inspection and condition rating, which includes the following attributes:

Appendix table 8-4: Historical inspection and condition rating

Attribute Name	Description	Type/ Domain
Inspection ID #	It is a unique ID # for each inspection record as the same segment could be having more than one inspection record in its' service life.	Code
Inspection date	It represents the date the inspection record was inputted.	Date
IRI	It represents the value of the international roughness index.	Numeric
Alligator cracking extent (%)	It represents extent of the alligator cracking. A percentage scale was used to represent the extent of alligator cracking in the whole highway.	Numeric
Rutting depth (mm)	It represents the rutting depth.	Numeric
PCI (%)	It represents the condition of the road. A percentage scale is used from 0 (failing condition) to 100 (excellent condition)	Numeric
Condition state	It represents the pavement condition state based on the PCI value.	Text

8.1.5 Past M&R Actions

The past M&R actions sub-module consists of all the information necessary to define the M&R actions of the highway. Appendix table 8-5 shows the information about the past M&R actions, which includes the following attributes:

Appendix table 8-5: Past M&R actions attributes

Attribute Name	Description	Type/ Domain
Maintenance ID #	It is a unique ID # for each maintenance record as the same segment could be having more than one maintenance record in its' service life.	Code
Maintenance date	It represents the date the maintenance record was inputted.	Date
Applied M&R strategy	It represents the M&R chosen strategy.	Numeric
PCI before M&R application	It represents the PCI before applying the M&R strategy.	Numeric
PCI after M&R application	It represents the PCI after applying the M&R strategy.	Numeric
IRI before M&R application	It represents IRI before applying the M&R strategy.	Numeric
IRI after M&R application	It represents the IRI after applying the M&R strategy.	Numeric
Surface rating before M&R application	It represents surface rating before applying the M&R strategy.	Numeric

Surface rating after M&R application	It represents the surface rating after applying the M&R strategy.	Numeric
Alligator cracking before M&R application	It represents alligator cracking before applying the M&R strategy.	Numeric
Alligator cracking after M&R application	It represents the alligator cracking after applying the M&R strategy.	Numeric

**8.2 APPENDIX B – KEY PERFORMANCE INDICATORS AND PENALTIES/INCENTIVES SYSTEM
INTRODUCED IN THE PERFORMANCE-BASED ROAD MAINTENANCE CONTRACT**

KPI ID #	KPI's	Main KPI Category	Allowable Limit	Units of Measurement
1	Surface Rating	Surface Rating	8	Surface Rating Range as per defined in the Actual Condition Rating Module
2	Rutting	Rutting	9.00	Millimeters (mm)
3	Alligator Cracking	Alligator Cracking	30%	Alligator Cracking extent of distribution on a percentage (%) scale as per defined in the Actual Condition Rating Module
4	International Roughness Index (IRI)	International Roughness Index (IRI)	2.60	Meter per Kilometer (m/km)
5	Pavement Condition Index (PCI)	Pavement Condition Index (PCI)	64%	Pavement Condition Index (PCI) percentage (%) scale as per defined in the Actual Condition Rating Module
6	Safety Considerations	Safety Considerations	60	Number of Accidents and its' severity level
7	User Costs	User Costs	EGP 5,000.00	Egyptian Pounds (EGP)
8	Potholes Response Time	Response Time	24	Hours
9	Barriers Response Time	Response Time	12	Hours
10	Guardrails Response Time	Response Time	12	Hours
11	Accidents Response time	Response Time	2	Hours
12	Maintenance Safety Considerations (Signs, Maintenance Time, Etc...)	Safety Considerations	10	Number of Accidents and its' severity level
13	End-User Satisfaction regarding the travel time, pavement safety, pavement quality, etc...	Customer Satisfaction	80%	Satisfaction percentage (%)

Appendix table 8-6: IHAMS KPIs'

KPI ID #	KPI's	Allowable Limit	Units of Measurement	Penalty (EGP)	Incentive (EGP)	Penalties Application Criteria	Penalties Application	Incentives Application Criteria	Incentives Application
1	Surface Rating	8	Surface Rating Range as per defined in the Actual Condition Rating Module	EGP 4,000.00	EGP 2,500.00	Applied whenever the maintenance contractor exceeds the defined limit	Penalty value per year	Applied after meeting the defined limits for 4 consecutive years	Incentive value per year
2	Rutting	9.00	Millimeters (mm)	EGP 5,000.00	EGP 3,000.00	Applied whenever the maintenance contractor exceeds the defined limit	Penalty value per year	Applied after meeting the defined limits for 4 consecutive years	Incentive value per year
3	Alligator Cracking	30%	Alligator Cracking extent of distribution on a percentage (%) scale as per defined in the Actual Condition Rating Module	EGP 2,000.00	EGP 1,500.00	Applied whenever the maintenance contractor exceeds the defined limit	Penalty value per year	Applied after meeting the defined limits for 4 consecutive years	Incentive value per year
4	International Roughness Index (IRI)	2.60	Meter per Kilometer (m/km)	EGP 6,000.00	EGP 4,000.00	Applied whenever the maintenance contractor exceeds the defined limit	Penalty value per year	Applied after meeting the defined limits for 4 consecutive years	Incentive value per year
5	Pavement Condition Index (PCI)	64%	Pavement Condition Index (PCI) percentage (%) scale as per defined in the Actual Condition Rating Module	EGP 0.00	EGP 0.00	Applied whenever the maintenance contractor exceeds the defined limit	Penalty value per year	Applied after meeting the defined limits for 4 consecutive years	Incentive value per year
6	Safety Considerations	60	Number of Accidents and its' severity level	EGP 200.00	EGP 400.00	Applied whenever the actual number of accidents per year exceeds the defined limit	Penalty value per year per additional accident	Applied whenever the actual number of accidents per year becomes less than the defined limit	Incentive value per year per reduced accident
7	User Costs	EGP 5,000.00	Egyptian Pounds (EGP)	EGP 2,000.00	EGP 1,200.00	Applied whenever the actual user costs exceeds the defined limit	Penalty value per year	Applied after meeting the desired limiting user costs for 2 consecutive years	Incentive value per year
8	Potholes Response Time	24	Hours	EGP 300.00	EGP 150.00	Applied whenever the maintenance contractor fails to respond within the defined response time	Penalty value per additional hour per pothole	Applied whenever the maintenance contractor succeeds to respond to the defect in a time less than the defined limit	Incentive value per reduced hour per pothole
9	Barriers Response Time	12	Hours	EGP 200.00	EGP 100.00	Applied whenever the maintenance contractor fails to respond within the defined response time	Penalty value per additional hour per barrier	Applied whenever the maintenance contractor succeeds to respond to the defect in a time less than the defined limit	Incentive value per reduced hour per barrier
10	Guardrails Response Time	12	Hours	EGP 200.00	EGP 100.00	Applied whenever the maintenance contractor fails to respond within the defined response time	Penalty value per additional hour per guardrail	Applied whenever the maintenance contractor succeeds to respond to the defect in a time less than the defined limit	Incentive value per reduced hour per guardrail
11	Accidents Response time	2	Hours	EGP 400.00	EGP 200.00	Applied whenever the maintenance contractor fails to respond within the defined response time	Penalty value per additional hour per accident	Applied whenever the maintenance contractor succeeds to respond to the defect in a time less than the defined limit	Incentive value per reduced hour per accident
12	Maintenance Safety Considerations (Signs, Maintenance Time, Etc...)	10	Number of Accidents and its' severity level	EGP 200.00	EGP 100.00	Applied whenever the actual number of accidents per year exceeds the defined limit	Penalty value per year per additional accident	Applied whenever the actual number of accidents per year becomes less than the defined limit	Incentive value per year per reduced accident
13	End-User Satisfaction regarding the travel time, pavement safety, pavement quality, etc...	80%	Satisfaction percentage (%)	EGP 800.00	EGP 800.00	Applied whenever the actual end-user satisfaction percentage (%) is less than the defined satisfaction percentage (%)	Penalty value per year	Applied whenever the actual end-user satisfaction percentage (%) exceeds the defined satisfaction percentage (%)	Incentive value per year

Appendix table 8-7: IHAMS P/I system

8.3 APPENDIX C – PROJECT-LEVEL IHAMS - INSPECTION SHEETS

Detailed Inspection Sheet

Highway Department _____ Street Name _____ District _____ File Ref. _____
 Region/Division Road Maintenance Detailed Inspector Segment # _____ Street Code _____ Date of Inspection _____
 Beginning _____ End _____ Section _____ Checked by _____
 KMs _____ Date of Checking _____

<p>F Flexible Defects</p> <p>FC Fine cracking BC Block cracking CC Crocodile/Alligator cracking DC Diagonal cracking LC Longitudinal cracking SC Slippage cracking TC Transverse cracking CR Corrugation DW Depression w/creaks DP Depression w/o cracks RU Rutting SV Shoving FL Flushing/Bleeding PO Polishing (Aggregates) RW Ravelling w/creaks RV Ravelling w/o cracks PH Potholes PT Patching BS Bumps and Sags EC Edge Cracking SD Shoulder Drop-off SW Swell HO Hazardous Obstruction</p> <p>Flexible Defects Severity Levels</p> <p>L Low</p> <p>M Medium H High</p>	<p>T Traffic Signs/Street Furniture</p> <p>BO Bollards CB Crash barrier CC Crash cushion DS Directional sign NP Street name plate PB Profile barrier PP Park meter post RA Railing RM Road marking RS Road stud TS Traffic sign</p> <p>Traffic Signs/Street Furniture Severity Levels</p> <p>D Damaged M Missing B Bent L Loose F Fade</p> <p>M Miscellaneous</p> <p>AS Antiskid surface worn ID Illegal dump UT Unreinstated trench</p> <p>V Verge</p> <p>DE Deterioration</p> <p>GL Grass too long</p>	<p>D Drainage/Utilities</p> <p>G Gully grating C Channel cover M Manhole/chamber cover P Ponding or flooding</p> <p>Drainage/Utilities Severity Levels</p> <p>D Damaged M Missing B Blocked S Sunken</p> <p>K Kerbs/Footway</p> <p>KB Defective kerb CK Crack DR Depression BD Block work defects RV Ravelling UN Uneven HO Hazardous obstructions</p>
--	--	---

	Summary Table
Category	Rating
Surface Rating Scale (0 - 10)	_____
Alligator Cracking Extent (%)	_____
Rutting Depth (mm)	_____
International Roughness Index - IRI (m/km)	_____

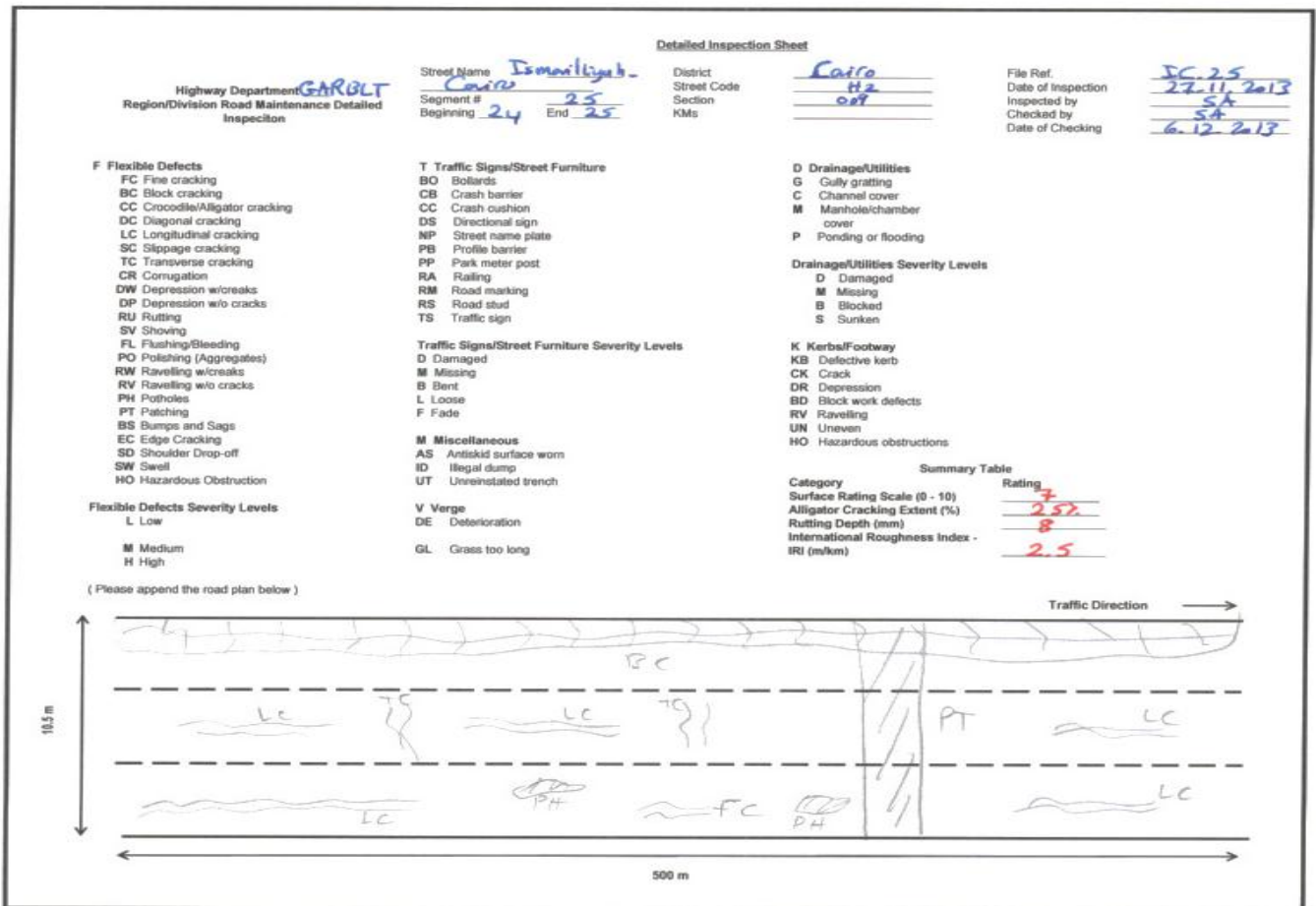
(Please append the road plan below)

Traffic Direction →

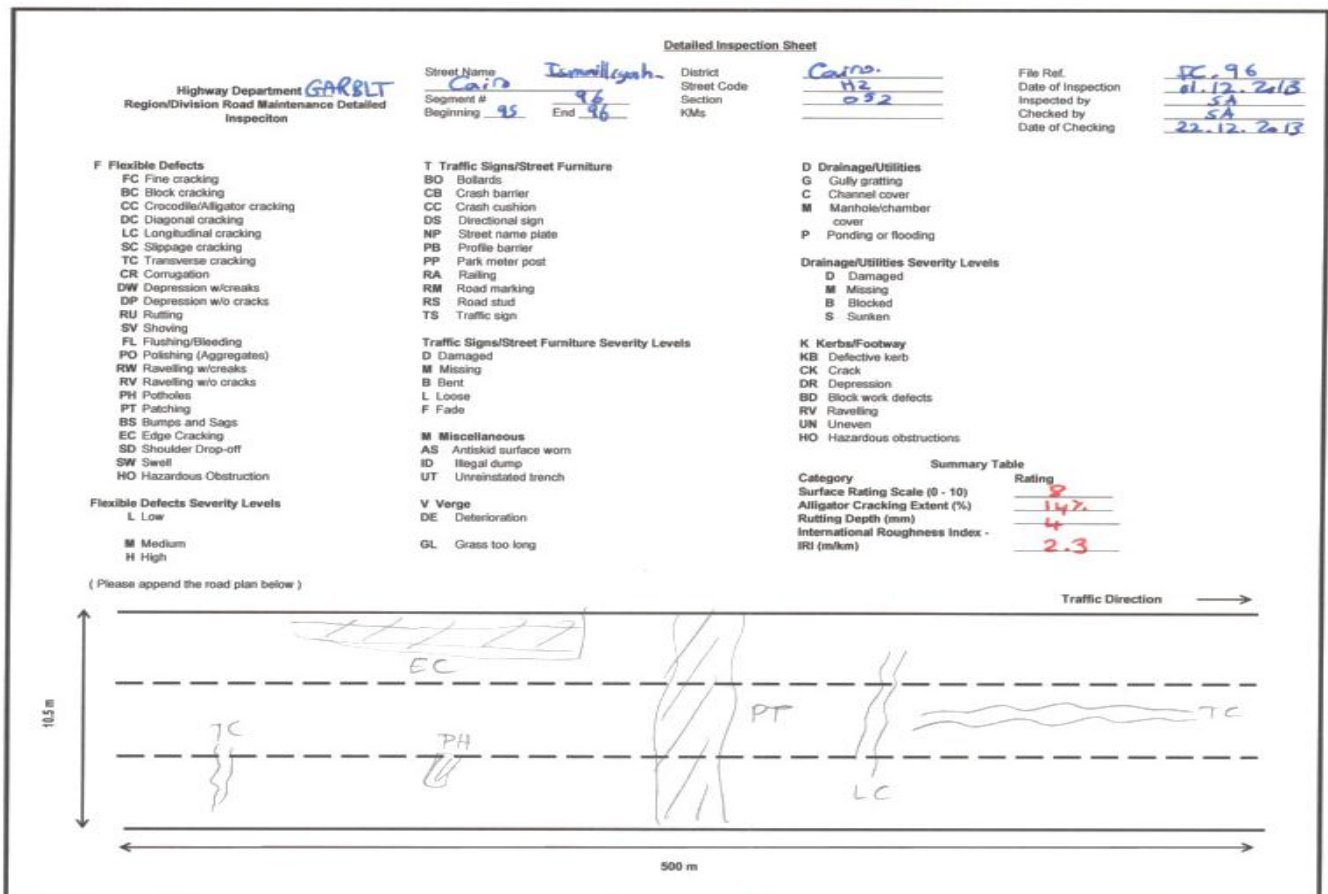
500 m

10.5 m

Appendix figure 8-1: IHAMS inspection sheet sample



Appendix figure 8-2: Sample inspection conducted on 6.12.2013 by the author



Appendix figure 8-3: Sample inspection conducted on 22.12.2013 by the author








8.4 APPENDIX D – PROJECT-LEVEL AND NETWORK-LEVEL IHAMS SCREENSHOTS

Automatic Coding ID	Country Name	Type of Road	Route Type	Qualifier	Pavement Configuration	Residence City Name	Destination City Name	Highway from Residence to Destination	State Highway Number	Highway Owner Agency	Highway Inspection Agency	Highway Maintenance Agency	Entry Date
EGYDIS01QAH20ISM01010001	Egypt	Highways	District Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	Al-Ḥmāṭīyah [Ismailia]	Desert Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYPRO03QAH20SWS0201010002	Egypt	Highways	Province Roads	Business Route	Divided	Al-Qāhira [Cairo]	As-Suways [Suez]	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYDIS05QAH20ISM03010020003	Egypt	Highways	District Roads	Truck Route	Divided	Al-Qāhira [Cairo]	Al-Ḥmāṭīyah [Ismailia]	Desert Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYREG03QAH10QLY04010020004	Egypt	Highways	Region Roads	Business Route	Divided	Al-Qāhira [Cairo]	Al-Qalyūbyah [Qalyubia]	Delta Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYPRO01QAH20ASW05010030005	Egypt	Highways	Province Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	Aswān	Desert Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYIST03QAH20BAH06010030006	Egypt	Highways	Interstate Roads	Business Route	Divided	Al-Qāhira [Cairo]	Al-Baḥr al-Aḥmar [Red Sea]	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYST05QAH10QLY07010040007	Egypt	Highways	State Roads	Truck Route	Divided	Al-Qāhira [Cairo]	Al-Qalyūbyah [Qalyubia]	Delta Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYST03QAH20ISM08010040008	Egypt	Highways	State Roads	Business Route	Divided	Al-Qāhira [Cairo]	Al-Ḥmāṭīyah [Ismailia]	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYDIS03QAH20SWS09020050009	Egypt	Highways	District Roads	Business Route	Divided	Al-Qāhira [Cairo]	As-Suways [Suez]	Desert Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYPRO01QAH20ISM10020050010	Egypt	Highways	Province Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	Al-Ḥmāṭīyah [Ismailia]	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYPRO03QAH10QLY11020060011	Egypt	Highways	Province Roads	Business Route	Divided	Al-Qāhira [Cairo]	Al-Qalyūbyah [Qalyubia]	Delta Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYST05QAH20ASW12020060012	Egypt	Highways	State Roads	Truck Route	Divided	Al-Qāhira [Cairo]	Aswān	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYPRO03QAH20BAH13020070013	Egypt	Highways	Province Roads	Business Route	Divided	Al-Qāhira [Cairo]	Al-Baḥr al-Aḥmar [Red Sea]	Desert Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYPRO01QAH10QLY14020070014	Egypt	Highways	Province Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	Al-Qalyūbyah [Qalyubia]	Delta Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYPRO01QAH20ISM15020080015	Egypt	Highways	Province Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	Al-Ḥmāṭīyah [Ismailia]	Desert Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYDIS01QAH20SWS16020080016	Egypt	Highways	District Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	As-Suways [Suez]	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYPRO03QAH20ISM17030090017	Egypt	Highways	Province Roads	Business Route	Divided	Al-Qāhira [Cairo]	Al-Ḥmāṭīyah [Ismailia]	Desert Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYDIS05QAH10QLY18030090018	Egypt	Highways	District Roads	Truck Route	Divided	Al-Qāhira [Cairo]	Al-Qalyūbyah [Qalyubia]	Delta Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYREG03QAH20ASW190300100019	Egypt	Highways	Region Roads	Business Route	Divided	Al-Qāhira [Cairo]	Aswān	Desert Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYPRO01QAH20BAH200300100020	Egypt	Highways	Province Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	Al-Baḥr al-Aḥmar [Red Sea]	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYIST01QAH10QLY210300100021	Egypt	Highways	Interstate Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	Al-Qalyūbyah [Qalyubia]	Delta Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYST01QAH20ISM220300100022	Egypt	Highways	State Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	Al-Ḥmāṭīyah [Ismailia]	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYST03QAH20SWS230300100023	Egypt	Highways	State Roads	Business Route	Divided	Al-Qāhira [Cairo]	As-Suways [Suez]	Desert Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYDIS05QAH20ISM240300100024	Egypt	Highways	District Roads	Truck Route	Divided	Al-Qāhira [Cairo]	Al-Ḥmāṭīyah [Ismailia]	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013
EGYPRO03QAH10QLY250400130025	Egypt	Highways	Province Roads	Business Route	Divided	Al-Qāhira [Cairo]	Al-Qalyūbyah [Qalyubia]	Delta Highway	Highway Number	GARBLT	GARBLT	Hassan Allam	15/11/2013
EGYPRO01QAH20ASW260400130026	Egypt	Highways	Province Roads	No Qualifier	Divided	Al-Qāhira [Cairo]	Aswān	Desert Highway	Highway Number	GARBLT	GARBLT	Arab Contractors	15/11/2013

Appendix figure 8-4: Sample of the location Identity sheet in the pavement inventory

Distress ID #	Distress Types	Units of Measurement	Distress Weight	Low Severity Level Percentage	Medium Severity Level Percentage	High Severity Level Percentage	Occasional Extent Level Percentage	Frequent Extent Level Percentage	Extensive Extent Level Percentage
1	Fine cracking	Crack width (mm)	5%	40%	70%	100%	50%	70%	100%
2	Diagonal cracking	Crack width (mm)	5%	40%	70%	100%	50%	70%	100%
3	Longitudinal cracking	Crack width (mm)	5%	40%	70%	100%	50%	70%	100%
4	Slippage cracking	Crack width (mm)	5%	40%	70%	100%	50%	70%	100%
5	Cracking Summation	Crack width (mm)	5%	40%	70%	100%	50%	70%	100%
6	Block cracking	Crack width (mm)	10%	40%	70%	100%	50%	70%	100%
7	Transverse cracking	Crack width (mm)	10%	40%	70%	100%	50%	70%	100%
8	Block and transverse cracking	Square meter (m ²)	10%	40%	70%	100%	50%	70%	100%
9	Corrugation	Ride Quality	5%	40%	80%	100%	50%	80%	100%
10	Flushing/Bleeding	Square meter (m ²)	5%	80%	80%	100%	60%	90%	100%
11	Polishing (Aggregates)	Visual Inspection	5%	80%	80%	100%	60%	90%	100%
12	Bleeding and Polishing Summation	Linear meter	5%	80%	80%	100%	60%	90%	100%
13	Raveling w/cracks	Square meter (m ²)	15%	30%	60%	100%	50%	80%	100%
14	Raveling w/o cracks	Square meter (m ²)	15%	30%	60%	100%	50%	80%	100%
15	Raveling Summation	Square meter (m ²)	15%	30%	60%	100%	50%	80%	100%
16	Potholes	Depth (mm) and Radius (mm)	15%	40%	70%	100%	50%	80%	100%
17	Patching	Square meter (m ²)	5%	30%	60%	100%	60%	80%	100%
18	Depression w/cracks	Depth (mm)	10%	50%	70%	100%	50%	80%	100%
19	Depression w/o cracks	Depth (mm)	10%	50%	70%	100%	50%	80%	100%
20	Shoving	Ride Quality	10%	50%	70%	100%	50%	80%	100%
21	Bumps and Sags	Ride Quality	10%	50%	70%	100%	50%	80%	100%
22	Settlements Summation	Overall Settlement	10%	50%	70%	100%	50%	80%	100%
23	Edge Cracking	Crack width (mm)	5%	40%	70%	100%	50%	70%	100%
24	Surface Rating	Overall Surface Rating	35%						
25	Crocodile/Alligator cracking	Square meter (m ²)	15%	40%	70%	100%	50%	70%	100%
26	Rutting	Depth (mm)	15%	30%	70%	100%	60%	80%	100%

Appendix figure 8-5: Distresses weights, severity and extent levels

Pavement Distresses Rating					
Rating	General Description	Frequency	Severity	Appearance	Illustration Picture
10	No distress, recently constructed or rehabilitated	No distress is present	-	New pavement, dark black and neat. Typically one year old or less	
9	No significant distress	All to nearly all of the pavement is free of distress; a single defect or crack per 0.16 Km is allowed	The defect is superficial or the crack is tight	Surface is typically oxidized to gray color. Typically one year old to three years old	
8	Infrequent distress, slight severity	Most of the pavement is free of cracking. Easy to count number of cracks at highway speed	Cracks are tight and very widely spaced. Neither secondary cracking nor dominant distresses are present	Surface looks uniform and neat	
7	Infrequent to occasional distress with minor severity	Much of the pavement is free of cracking. More difficult to count number of cracks but still possible	Crack's width is mostly less than 3.2 mm and may have secondary cracking. No to very little connected cracks and it may have an isolated dominating distresses	Looks fairly good but cracking is noticeable	
6	Occasional to frequent distress with moderate severity	Much to most of the pavement is cracked. Cracks are spaced only a few meters apart or less	Crack's width varies from tight to greater than 3.2 mm wide. Most cracks have secondary cracking and cracks are extending to connect with adjacent cracks and a dominating distresses may occur	Condition looks "Fair"	
5	Distress is frequent and moderate to severe	Nearly all the pavement or wheel paths have multiple, well developed cracks	Cracks are wide and/or well developed with secondary cracking. Many cracks are interconnected. Pieces of pavement are dislodged or have been patched	Condition looks "Poor"	
4 or less	Distress is frequent and severe	Pavement is mostly cracked and travel on the pavement is impaired	Cracks are wide and connected. Potholes and/or patches are common. Patches on patches are apparent	Condition looks "Failing"	

Appendix figure 8-6: Surface rating system with illustrative pictures (NYSDOT, 2010)

Maintenance Type	Definition	When Applied	Preferable Pavement Condition Index (PCI)
New Construction	Pavement new construction is "the construction of a new pavement structure."	Pavement new construction is applied for constructing a new pavement structure.	-
Reconstruction	Pavement Reconstruction is "the replacement of the entire existing pavement structure by the placement of the equivalent or increased pavement structure."	Reconstruction usually requires the complete removal and replacement of the existing pavement structure. Reconstruction may utilize either new or recycled materials incorporated into the materials used for the reconstruction of the complete pavement section. Reconstruction is required when a pavement has either failed or has become functionally obsolete.	Less than 25
Major (Heavy) Rehabilitation	Major rehabilitation "consists of structural enhancements that both extend the service life of an existing pavement and/or improve its load-carrying capability."	Rehabilitation projects extend the life of existing pavement structures either by restoring existing structural capacity through the elimination of age-related, environmental cracking of embrittled pavement surface or by increasing pavement thickness to strengthen existing pavement sections to accommodate existing or projected traffic loading conditions.	Between 40 and 25
Structural Overlay	Structural Overlay is "used to cover the pavement surface with another structural layer for the purpose of increasing the pavement structural capacity and correct the surface deficiencies."	Structural overlays are used to increase pavement structural capacity and correct any surface deficiencies.	Between 40 and 25
Minor (Light) Rehabilitation	Minor rehabilitation "consists of non-structural enhancements made to the existing pavement sections to eliminate age-related, top-down surface cracking that develop in flexible pavements due to environmental exposure."	Rehabilitation projects extend the life of existing pavement structures either by restoring existing structural capacity through the elimination of age-related, environmental cracking of embrittled pavement surface or by increasing pavement thickness to strengthen existing pavement sections to accommodate existing or projected traffic loading conditions.	Between 50 and 40
Preventive Maintenance	Preventive Maintenance is "a planned strategy of cost-effective treatments to an existing roadway system and its appurtenances that preserves the system, retards future deterioration, and maintains or improves the functional condition of the system (without significantly increasing the structural capacity)."	Preventive maintenance is typically applied to pavements in good condition having significant remaining service life. Preventive maintenance is a strategy of extending the service life by applying cost-effective treatments to the surface or near-surface of structurally sound pavements.	Between 100 and 50
Routine Maintenance	Routine Maintenance "consists of work that is planned and performed on a routine basis to maintain and preserve the condition of the highway system or to respond to specific conditions and events that restore the highway system to an adequate level of service."	Routine maintenance consists of day-to-day activities that are scheduled by maintenance personnel to maintain and preserve the condition of the highway system at a satisfactory level of service.	Between 100 and 50
Corrective (Reactive Maintenance)	Corrective Maintenance activities "are performed in response to the development of a deficiency or deficiencies that negatively impact the safe, efficient operations of the facility and future integrity of the pavement section."	Corrective maintenance activities are generally reactive, not proactive, and performed to restore a pavement to an acceptable level of service due to unforeseen conditions.	Between 100 and 50
Catastrophic Maintenance	Catastrophic Maintenance "describes work activities generally necessary to return a roadway facility back to a minimum level of service while a permanent restoration is being designed and scheduled."	Very late time to return the pavement back to a minimum level of service	Less than 40

Appendix figure 8-7: Maintenance strategies definition and PCI limits

Overall Pavement Condition Index Calculator								
Items	Surface Rating	Surface Rating year	Alligator Cracking	Alligator Cracking year	Rutting	Rutting Conversion mm to in	International Roughness Index (IRI)	IRI Conversion m/Km to in/mile
Inputs	6	2nd Year or More	Alligator cracking - Less than 20%	2nd Year or More	6	0.04	5	0.02
Deducting Values	20%		8%		2%		35%	
Pavement Condition Index (PCI)	34%							
Pavement Condition Index (PCI)	Very Poor							

PCI Range	Pavement Condition Rating	Color Scale	Colors
100 - 85	Excellent	Dark Green	
85 - 70	Good	Light Green	
70 - 55	Fair	Yellow	
55 - 40	Poor	Ligh Red	
40 - 25	Very Poor	Medium Red	
25 - 10	Serious	Dark Red	
10 - 0	Failed	Dark Grey	

IRI Value (m/Km)	Comfortable Ride Speed (km/hr)	General Description
0 - 2	Over 120 Km/hr	Very smooth
2 - 4	100 Km/hr to 120 Km/hr	Smooth
4 - 6	70 Km/hr to 90 Km/hr	Perceptible movement
6 - 8	50 Km/hr to 60 Km/hr	Some swaying and wheel bounce
8 - 10	40 Km/hr to 50 Km/hr	Significant swaying
10 - 12	30 Km/hr to 40 Km/hr	Consistently rough
12 - 14	< 30 Km/hr	Very rough

IRI Category	Color Scale
Excellent	
Good	
Fair	
Poor	
Very Poor	

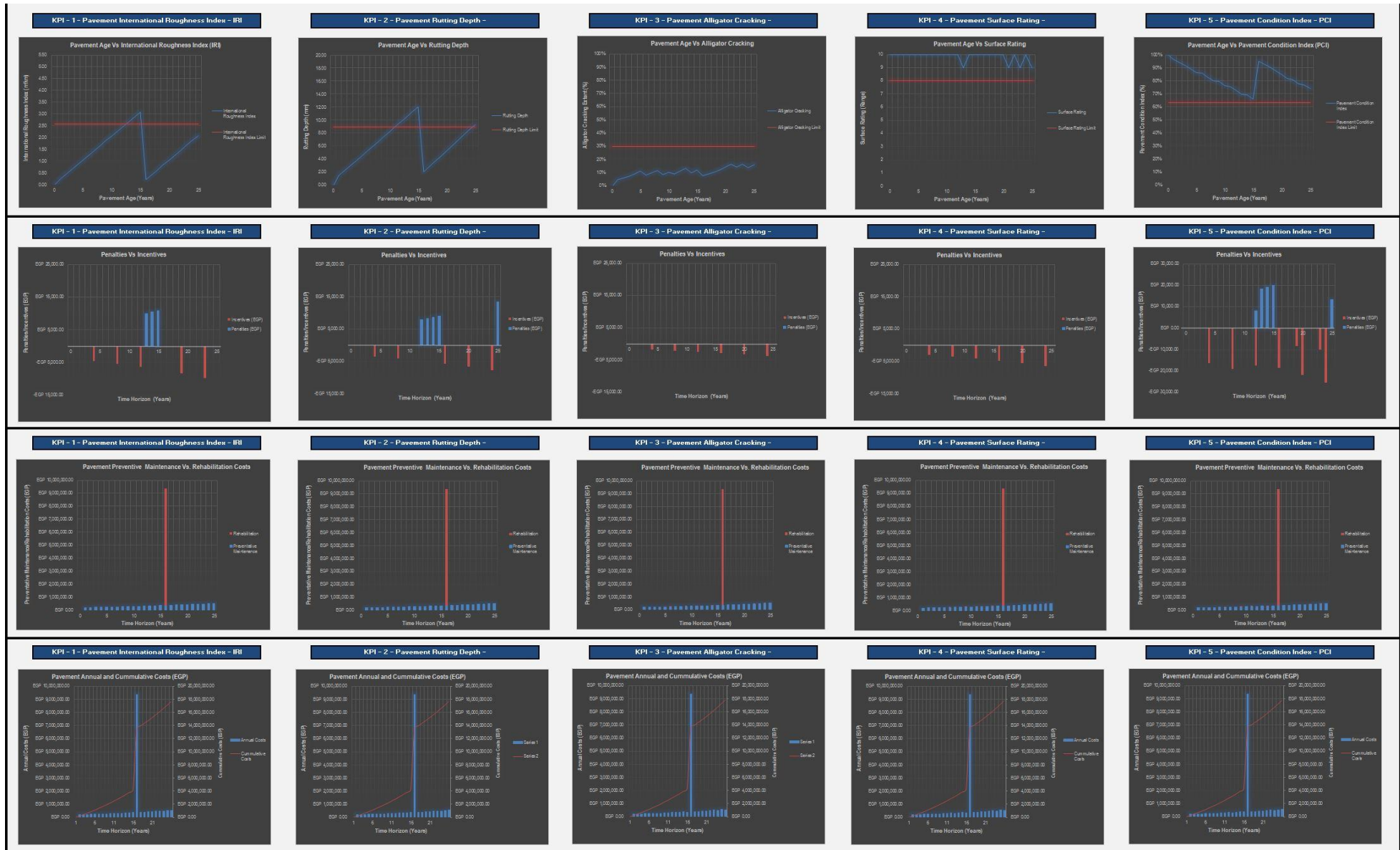
Go back to the organization sheet

Go to the Asset Inventory - Maintenance and Rehabilitation

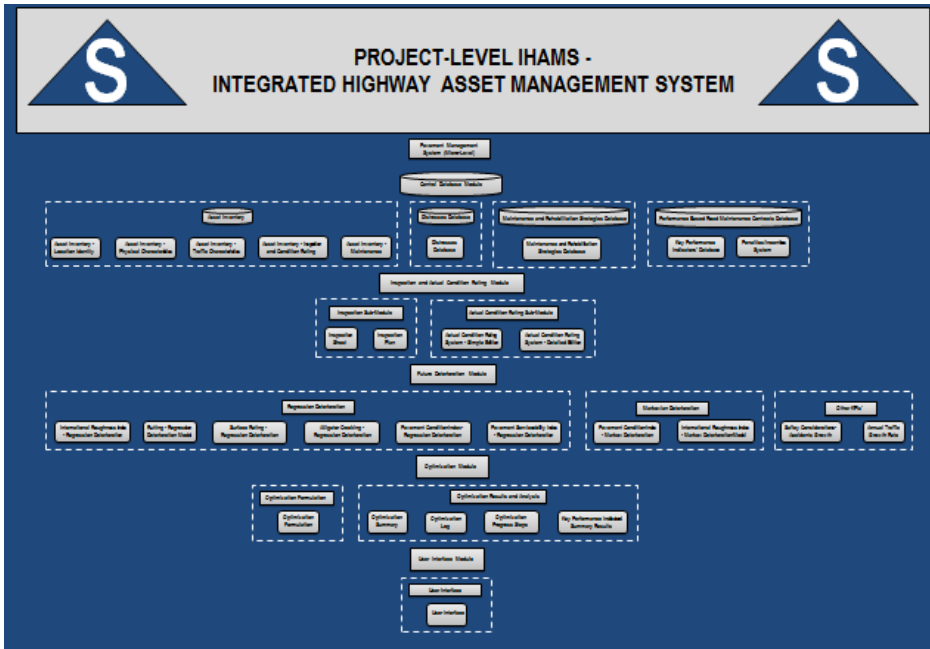
Appendix figure 8-8: PCI and IRI condition rating system (NYSDOT, 2010)

Decision Variable ID #	Maintenance Strategies	Decision Cost (EGP)	Decision Cost Units of Measurement	Decision effect on IRI	Decision effect on Rutting	Decision effect on Surface Rating	Decision effect on Alligator Cracking
0	Do Nothing	EGP 0.00	-	-	-	-	-
1	Crack Sealing	EGP 25.00	Linear Meter (m')	0%	0%	40%	40%
2	Slurry Sealing	EGP 40.00	Linear Meter (m')	0%	0%	45%	50%
3	Micro-surfacing	EGP 65.00	Square Meter (m ²)	50%	0%	50%	0%
4	Thin Overlay	EGP 80.00	Square Meter (m ²)	60%	0%	60%	55%
5	Structural Overlay	EGP 95.00	Square Meter (m ²)	70%	0%	70%	65%
6	Patching	EGP 100.00	Square Meter (m ²)	0%	0%	75%	75%
7	Milling and filling	EGP 110.00	Square Meter (m ²)	90%	60%	80%	0%
8	Deep patching	EGP 160.00	Square Meter (m ²)	0%	85%	85%	85%
9	Reconstruction	EGP 180.00	Square Meter (m ²)	95%	95%	95%	95%

Appendix figure 8-9: M&R decision variables costs and effect on KPIs'



Appendix figure 8-10: Project-level KPIs' graphical presentation



Simple PCI Calculator	Surface Rating 10	Surface Rating year 2nd Year or More	Alligator Cracking Alligator cracking - Less than 20%	Alligator Cracking year 2nd Year or More	Rutting depth (mm) 3.00	International Roughness Index (IRI) 2.00
Detailed PCI Calculator	Fine cracking (Appearance) Yes	Fine cracking width (mm) 7.00	Fine cracking extent (%) 50%	Cracking Extent (%) 50%	Diagonal cracking (Appearance) No	Diagonal cracking width (mm) 12.00
Inspection Data	Total number of sample units (N) 200	Required Confidence Interval (%) 95%	Allowable Error percentage (%) 5%	Standard Deviation of the PCI (σ) 8		
Future Condition Prediction	Road Constructed in Year 1/1/2005	Year for Prediction 1/1/2025	Age (Years) 20			

Number of Samples to be surveyed (n)	10
Number of Additional Samples (a)	1
Total Number of Samples (n+a)	11

KPI 1 - International Roughness Index (IRI) - (m/km)	1.04	Total Annual Costs (EGP)	EGP 416,422.95
KPI 2 - Rutting Depth (mm)	5.21	Penalties (EGP)	EGP 0.00
KPI 3 - Surface Rating	10	Incentives (EGP)	EGP 21,801.68
KPI 4 - Alligator Cracking Extent (%)	14%		
KPI 5 - Pavement Condition Index - PCI (%)	85%		

Appendix figure 8-11: Project-level IHAMS user interface

**NETWORK-LEVEL IHAMS -
INTEGRATED HIGHWAY ASSET MANAGEMENT SYSTEM**

Newest Report
User Information

Report IRI

IRI 1 IRI 2 IRI 3 IRI 4 IRI 5

Report CR

CR 1 CR 2 CR 3 CR 4 CR 5

Report PCI

PCI 1 PCI 2 PCI 3 PCI 4 PCI 5

Report RDI

RDI 1 RDI 2 RDI 3 RDI 4 RDI 5

Report SRI

SRI 1 SRI 2 SRI 3 SRI 4 SRI 5

Compare Data

Compare Penalties

Penalties 1 Penalties 2 Penalties 3 Penalties 4 Penalties 5

Compare Rehabilitation

Rehab 1 Rehab 2 Rehab 3 Rehab 4 Rehab 5

User Information

Log Out

Pavement Future Condition Prediction

Pavement ID #	Year of Construction	Year for Prediction	Age (Years)
Pavement 4	1/1/2005	1/1/2015	10

Network Future Condition Prediction

Network ID #	Year for Prediction	Age (Years)
Network 1	1/1/2015	10

Predict the future Key Performance Indicators (KPIs) for a single pavement in the network

Predict the overall network condition index and the future maintenance and rehabilitation costs

KPI 1 - International Roughness Index (IRI) - (m/km)	2.06	Total Annual Costs (EGP)	EGP 316,772.28
KPI 2 - Rutting Depth (mm)	8.21	Penalties (EGP)	EGP 0.00
KPI 3 - Surface Rating	10	Incentives (EGP)	EGP 0.00
KPI 4 - Alligator Cracking Extent (%)	7%		
KPI 5 - Pavement Condition Index - PCI (%)	78%		

Go back to main user interface

Predict the overall network condition index and the future maintenance and rehabilitation costs

Network Condition Index - NCI (%)	77.56%	Network Incentives (EGP)	EGP 0.00
Network Preventive Maintenance Costs (EGP)	EGP 1,480,244.28	Total Network Annual Cost (EGP)	EGP 1,521,691.12
Network Rehabilitation Costs (EGP)	EGP 41,446.84		
Network Penalties (EGP)	EGP 0.00		

Go back to main user interface

Predict the future Key Performance Indicators (KPIs) for a single pavement in the network

Appendix figure 8-12: Network-level IHAMS user interface