Risk and Reliability-Based Maintenance for Highway Infrastructure Asset Management

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A thesis submitted in partial fulfilment of the requirement of University of Greenwich for the degree of Doctor of Philosophy

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DECLARATION

I certify that this work has not been accepted in substance for any degree, and is not concurrently being submitted for any degree other than that of Doctor of Philosophy been studied at the University of Greenwich. I also declare that this work is the result of my investigation except where otherwise identified by references and that I have not plagiarised the work of others.

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DEDICATION

I bestow this work to my Creator-Father, the GOD Almighty in Heaven and Heroes of Faith "With me, this is impossible, but with God all things are possible'' … Matthew 19:26.

ABSTRACT

The highway industry, a critical section of Nigeria surface transportation industry is in pressing need of methods that would enable the reliability and maintainability of their fielded system. The availability and safety of highway infrastructure is a primary objective of an economy in other to provide a satisfactory level of service to road users and overcome the practical challenges from dissimilar highway assets. A large proportion of highway assets in Nigeria are classified as structurally deficient and functionally obsolete due to low discernibility of their functional failures, condition assessment and maintenance programmes which are often neglected until a catastrophic failure occurs. This research attempt to reveal ways for sound decision making to address the functional failures and structural defects and deterioration associated with highway assets by utilising UK datasets. The functional failures and structural deterioration defects are amongst the leading causes of growing failure probabilities of the road systems and networks. Thus, asset maintenance intervention is an essential task for the unified management of road assets and systems.

The objectives of this research are to evaluate and develop appropriate methods that could support asset management and maintenance strategies of highway infrastructure asset and systems. A qualitative approach was initiated to develop a preventive maintenance strategy using a reliability centred maintenance approach to propose a maintenance plan for the newly fielded highway system capturing key highway assets. After that quantitative techniques such as risk-based inspection, reliability growth analysis, Markov Chain deterioration modelling and treatment renewal costing were piloted using real-time UK highway maintenance data sets from Network Maintenance Management System (NMMS) and highway condition data from Surface Condition Assessment of National Network of Roads (SCANNER) Survey. Illustrations are presented to validate the proposed methods for preventing functional failure occurrences and deterioration of highway asset by prioritising maintenance based on failure severity and system reliability. The proposed risk and reliability-based maintenance approaches can be utilised when forming a preservation strategy to avoid the functional failure and decadence of fielded highway assets.

PUBLISHED WORK

Journal Publications

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ABBREVIATION

AM	Asset Management
AMS	Asset Management System
ASCE	America Society of Civil Engineers
CAS	Condition Assessment States
CBM	Condition-Based Maintenance
CBR	Case-Based Reasoning
CD	Condition Directed
CDF	Cumulative Distribution Function
CMMS	Computerised Maintenance Management System
CPD	Cumulative Probability Distribution
CS	Current State
CVI	Coarse Visual Inspection
CY	Current Year
DfT	Department for Transport
DVI	Detailed Visual Inspection
EDRG	Economic Development Research Group
EP	Event Plot
EPP	Extended Poisson Process
FMEA	Failure Mode Effect Analysis
FMECA	Failure Mode Effect and Criticality Analysis
FY	Future Years
GP	Geometric Process
HAMP	Highway Asset Management Plan
HPP	Homogeneous Poisson Process
IAM	Institute of Asset Management
IC	Improvement Condition
IET	Institute of Engineering & Technology
LSE	Least Square Estimate
LTP	Linear Transition Probability
MCF	Mean Cumulative Function
MIMAR	Modelling in Industrial Maintenance and Reliability
ML	Median Life
MLE	Maximum Likelihood Estimation
MTBF	Mean Time Between Failure
MTTF	Mean Time to Failure
MTTR	Mean Time to Repair
NHPP	Non-Homogeneous Poisson Process
NMMS	Network Maintenance Management System
PDF	Probability Density Function
PM	Preventive Maintenance

PY	Previous Year
RB	Road Barriers
RBI	Risk-Based Inspection
RBM	Risk-Based Maintenance
RCI	Road Condition Indicator
RCM	Reliability Centred Maintenance
RL	Road Lighting
RM	Road Markings
RP	Renewal Process
RS	Road Signs
SCANNER	Surface Condition Assessment of National Network of Roads
SCRIM	Sideway-force Coefficient Routine Investigation Machine
SI	Safety Inspection
TD	Time Directed
TfL	Transport for London
TRF	Time to Risk Failure
TS	Traffic Signals
TTT	Total-Time-on-Test
UKPMS	United Kingdom Pavement Management System

NOMENCLATURE

A	Safety and environment
B	Mission
C	Others
D	Hidden failures
α	Scale Parameter
β	Shape Parameter
λ	Threshold parameter/ Constant failure intensity
μ	Mean
σ	Standard deviation
σ^2	Variance
In^{date}	Defect investigatory inspection date
Re^{date}	Date of repair of the defect
$Defect^{period}$	Asset defective period
B_n	Condition band
B_T	Summation of condition band
FY_s	Future years
S_n	System one-step transition
S_t	System current state
S_{t+1}	System nth step transition
S_{CY}	Current year
S_{PY}	Previous year
P	Transition probability
P_{ij}	State change transition probability
P_{jj}	A same state transition probability
P_{LTP}	Linear transition probability
A_s	Area of Sample
C_b	Condition band
C_s	Current state
F_s	Forthcoming state
P_T	Performance transition
T_c	Treatment cost

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CHAPTER 1: INTRODUCTION

1.1 BACKGROUND OF STUDY

Highway infrastructures are vital for a nation's economic well-being and are often the most valuable asset for most government authorities. The Code of Practice for the maintenance of highway structures portrays that the vital importance of a well-maintained and managed highway infrastructure is about bringing better economic, social and environmental happiness of any country (UK Bridges Board, 2005). The catastrophic effect and consequences which often lead to issues such as reduced system safety decreased asset availability, short asset lifetime and increased whole life cycle cost are as a result of the lack of asset management solutions. The likelihood of asset failure and budget challenges can be decreased by the application of asset management tools (Vinnaria and Hukkab, 2010; Remenyte-Prescott and Andrews, 2013). According to the UK Roads Board (2005), a well-maintained highway would benefit from an asset management system, because the management of highway maintenance needs to be set within the context of an overall asset management regime.

The cost to achieve safety, serviceable and sustainable highway infrastructure has great depth in a nation's economy. Economic challenges facing highway owners varies from cost, delivery, reliability, quality assurance and technological capacity (Mehmann and Teuteberg, 2016). An asset management structure could help achieve a safe and cost-effective highway infrastructure system from asset conception, operation, inspection, maintenance, renewal, and disposal. The management of highway maintenance is best effective when set within the context of an asset management framework. Frameworks help provide the means of understanding the value and liability of the asset, giving authorities and asset owners a better understanding of the asset condition and in taking a right strategic decision (UK Roads Board, 2005). Having a highway asset management plan is fundamental to demonstrating the value of highway infrastructure and in delivering the broader objectives of the corporate strategy, transport policy and value for money (Highways Maintenance Efficiency Programme, 2013).

The highway assets of the road network often handle more traffic than they are designed for, therefore requiring a sophisticated road traffic management system together with reliability-based asset maintenance and management approach. Highway asset and elements are multifaceted physical assets that consist of different road infrastructure (e.g., pavement system, safety systems, traffic system, lighting systems, road surface systems). In consideration of the complexity of the various disparate highway assets, a mere technique is not feasible to carry out adequate maintenance. Instead, a more strategic procedure would be required with consideration of the various highway asset types, diverse functions, intermittent functional failures, and random deterioration pattern. The functional failure and gradual deterioration of highway assets are hazardous to any economy surface transport system because its effect diffuses throughout its entire networks. The effect of highway assets in their poor condition with continuous functional failures leads to increased operating cost, longer travel time and damage to the vehicle to road users (Economic Development Research Group, 2013).

The endless round the clock usage highway infrastructures often lead to degradation due to ageing and advent of weather conditions. A policy report by the Department for Transport and Highways Agency (2015) in the United Kingdom on managing, improving and investing in road network depicts that increased congestion and journey disruption results from a shortage of highway assets. It further said that the availability of ancillary highway assets such as road signs, traffic signals and road markings are vital for road safety and efficient use for road users by the timely information provided by them. The tailbacks arising from road congestion, increased rate of hazard and accident are most often the results of the unavailability or failure of these highway assets. In addition to this debacle, it could be perceived that the shortfall of adequate investment towards maintenance would continue, thus affecting the expected necessary funding for upholding the continuous functionality of these highway infrastructures to promote its socio-economic development purpose. Surface transportation needs have an enormous weight due to the high cost of the creation and operation associated with highway infrastructure assets (e.g. roads, bridges, and flyovers).

An annual local authority road maintenance survey by the Asphalt Institute Alliance (2012) indicates that there has been significant shortfall investment towards maintenance in the transport industry in the past ten years to a tune of one billion British Pounds Sterling (GBP) yearly. Periods of underfunding in the highway industry drive the maintenance of highway assets from planned preventive maintenance regimes to an increased reactive maintenance approach. A study steered by the Economic Development Research Group (EDRG), funded by the America Society of Civil Engineers (ASCE) ranks surface transportation as having the highest increasing infrastructure cost in America's economic future, categorising highway infrastructures as a key player of surface transportation. The analysis piloted by the EDRG as expressed in Table 1.1 accounts that surface transportation could face a funding gap of US$3,664 trillion by the year 2040. Conversely, all the other sector combined requires less US$1,017 billion (e.g. water/wastewater USD144 billion, electricity USD732 billion, airports US$95 billion, Inland Waterway & Marine ports US$46 billion) in the anticipated funding shortfall, simultaneously leading to the most significant impact to cost of business and household. (EDRG, 2013).

Table 1-1 United State Infrastructure needs Projection for the Year 2020 and 2040

Cumulative Infrastructure Needs using Current Trends (US$ in Billions)						
	TOTAL NEED		**LIKELY FUNDING**		**FUNDING GAP**	
	2020	**2040**	**2020**	**2040**	**2020**	**2040**
Surface transportation	$1723	$6751	$877	$3087	$846	$3664
Water /wastewater	$126	$195	$42	$52	$84	$144
Electricity	$736	$2619	$629	$1887	$107	$732
Airports	$134	$404	$95	$309	$39	$95
Inland waterway's	$30	$92	$14	$46	$16	$46
TOTALS	$2,749	$10,061	$1,657	$5,381	$1,092	$4,681

Source: (Economic Development Research Group, 2013)

The report further revealed that in addition to the public safety issue associated with deteriorating, failed and inadequate infrastructure; there is the possibility of cascading impact on the economy which negatively affects its business, employment, Gross Domestic Product (GDP), and personal income of the nation internationally. It projected that deficiencies are expected to cost the United State national economy collectively approximately US$900 billion in GDP, rising to US$2.7 trillion through 2040. With the predicted increase in the cost of business and household from the effect of degrading infrastructure a total tune of US$911 dollars in the year 2020 and US$2,972 trillion in the year 2040 as shown in Table 1.2.

Table 1-2 Projected Degrading Cost to Economy in the US for the year 2020 and 2040

Cumulative Infrastructure Needs Based on Current Trends (US$ in Billions)						
	HOUSEHOLDS		**BUSINESSES**		**TOTAL**	
	2020	**2040**	**2020**	**2040**	**2020**	**2040**
Surface transportation	$481	$1880	$430	$1092	$911	$2972
Water /waste water	$59	$616	$147	$1634	$206	$2250
Electricity	$71	$354	$126	$640	$197	$994
Airports	-	-	$258	$1212	$258	$1212
Inland waterway’s	-	-	$258	$1233	$258	$1233
TOTALS	$611	$2850	$1219	$5811	$1830	$8661

Source: (Economic Development Research Group, 2013)

It is likely that most economies rely on the reliable delivery of clean water and electricity to household and business at the low cost of production, however, if surface transportation systems worsen, there is a likelihood of an increase in prices in other sectors. The National Infrastructure Commission (NIC) which was set up to address problems with long-term infrastructure planning in the United Kingdom covers keys sectors of the UK economic infrastructure. The report on national infrastructure assessment by NIC (2018) portrays the substantial pressure the significant growth of the UK’s population and economy may face. Sectors captured in the report consists of transport, energy, water and wastewater, flood resilience, digital connectivity, and solid waste. Projected public capital expenditure of the UK economic infrastructure which is consistent with and accommodated within the UK gross public investment economic infrastructure as presented in Table 1.3. The Table 1.3 which projects the annual expenditure on infrastructure between 1.0% and 1.2% of GDP for every 5years between 2020 and 2040, is expanded to capture the transport system expenditure only and presented in Table 1.4

Table 1-3 Projected annual expenditure on Infrastructure in the UK

Cumulative average annual expenditure on infrastructure systems (GBP in millions)				
	2020-2025	**2025-2030**	**2030-2035**	**2035-2040**
Transport	24440	26,800	29,100	27,500
Housing infrastructure fund	500	200	200	200
Energy: Energy efficiency	100	300	300	100
Digital: Rural fibre	500	300	300	-
Waste	600	500	500	-
Flood resilience	600	700	700	500
Study contingency	300	400	400	1300
Total expenditure	26,900	29200	31,500	29,600
As a % of GDP	1.2%	1.2%	1.2%	1.0%

Table 1-4 Projected average expenditure on Transport Systems in the UK

Cumulative average annual expenditure on transport infrastructure (GBP in millions)				
TRANSPORT	**2020-2025**	**2025-2030**	**2030-2035**	**2035-2040**
HS2	4,500	3,900	900	-
Cross rail 2	200	2,200	2,900	-
Northern powerhouse rail	200	1,100	1,700	1,800
Network rail	6,100	6,100	-	-
Highways England	4,300	3,200	-	-
Strategic Transport (road & rail)	-	-	10,500	11,400
Devolved cars	3,300	3,600	4,600	5,400
Transport for London	2,600	2,900	2,200	2,000
Urban major projects	500	400	2,400	3,100
Non-urban local projects	2,700	2,900	3,400	3,800
Local roads Backlog	-	500	500	-
Total expenditure	24,400	26,800	29,100	27,500

Source: (National Infrastructure Commission, 2018)

The analysis of the national infrastructure assessment by NIC (2018) consists of new infrastructure projects, existing commitments to the UK economic infrastructure and ongoing investments in renewals and maintenance acknowledged the transport sector in the UK to experience the highest infrastructure need in the new future. It says an estimated investment in urban transport to the tune of GB£4 billion per year (2020 -2025) for Highways England, GB£6 billion per year (2019 -2024) for Network rail and GB£4 billion per year (2020 -2030) for the high-speed train. The recommendation from the report on transport infrastructure considered in Table 1.3 is presented in Tables 1.4 on how the various transport needs are shared out.

The categories of infrastructure systems analysed in the preceding reports from the US, Failure to Act (EDRG, 2013) and the UK, national infrastructure assessment NIC (2018) were reviewed in isolation by each study. However, it is clear that there is an interactive effect between different infrastructure sectors and the cumulative impact of the ongoing investment. In retrospect of the research challenge which encompasses Nigeria expenditures and economic resources. In the report by the International Project Finance Association (IPFA 2015) titled Unlocking Rapid Development of Transport Infrastructure in Nigeria, portraying the current state assessment of Nigeria Infrastructure has presented by the National Integrated Infrastructure Master Plan (NIIMP). The NIIMP identifies the funding gap in Nigeria's infrastructure in which optimal funding mix will be determined around bridging this funding gap. A holistic and well-thought of the plan will be required to guide implementation across various infrastructure projects and implementation of this plan will move Nigeria's transport infrastructure from the current state to the level of its peers

Nigeria's expenditure on transport infrastructure as of 2013 stood at USD 2.3 Billion. This level of expenditure has created a funding gap of US$ 800 Billion which can be covered over the next 30 years according to the NIIMP. In line with this, US$22 Billion is needed over the next 4 years translating to an average of US$5 Billion per annum. Nigeria has the largest road network in West Africa and the second largest, south of the Sahara with an estimated 200,000km of road network connecting villages to cities. The 2015 Global Competitiveness

Index of the world economic forum ranked the quality of Nigeria's road infrastructure at 125th out of 144 countries with road sector accounting for the lion's share of the required transport infrastructure investments. Over the 30 years of the NIIMP projection, total investment required is US$350 Billion for upgrading and expansion of existing road structure as shown in Table 1.5

Table 1-5 Nigeria Infrastructure spend requirements over the next 30 years

Transport Sector	**Funding Requirements**	
	(USD Billion)	**Naira (Trillions) Approx.**
Roads	350	127.07
Urban Mass Transit	250	90.76
Railway	75	27.26
Maritime	50	18.15
Aviation	50	18,15
Maintenance Cost over the period	37	13.44
TOTAL	812	294.98

Source: (International Project Finance Association, 2015)

1.2 HIGHWAY ASSET MAINTENANCE PROBLEM IN NIGERIA

A nation's transport infrastructure support the development of its society by providing the services essential to sustaining a vibrant economy. However, managing the highway network in such a way to ensure that it serves the economy and also provides the asset owners with continuous value poses several challenges that could lead to negative consequences if not adequately maintained. Adverse effects that developed from failing road infrastructure or poorly maintained transport network undermine any nation's economic growth and leads to increased highways accident mortality rate. A compendium report by the Nigeria Federal Ministry of Works (2013) reflects the resultant effect of the poorly maintained Nigeria road network, whose ailing infrastructure systems have caused several losses of lives and higher cost of living. Also, the compendium report stated that Nigeria economy loses approximately N350 billion annually, through deplorable road conditions causing the economy dearth of N175 billion. N88 billion loss due to increased vehicle operating costs. N12 billion loss due to delayed turnaround and increased travel time and N75 billion loss due to a reduction in asset value.

Poorly maintained and degrading highway infrastructure attracts higher inadvertent related situations, yielding severe traffic snare affecting road users and the environments. The frequency of repair works and service interruptions on the road network are caused by defects which lead to increased risk to road users (Orugbo, 2013). Trend analysis of fatal traffic accidents in Nigeria between June 2006 and May 2014 by Ukoji (2014) speculates that serious traffic accidents in 3,075 events took about 15,090 lives. The fatality occurred highest in 2013 (2,061 deaths), a 2.8% increase from the 2012 record of 1,652 deaths. This PhD research study whose focus is on risk and reliability-based maintenance methods and applications on highway assets would help remove the bottleneck associated with highway infrastructure and network hazards in exchange for highway network improvements. Highway network improvements activities are to help to eliminate the bottleneck associated with road congestion, reduce road hazards, install new technologies to improve driver's information and reduce incident clear up time (Fitzpatrick, 2013).

It is detrimental not to include, uphold and integrate the benefit of asset management into highway maintenance practices. Road network owners and administrators, like other surface transportation infrastructure owners, are continually considering all opportunities for trimming unnecessary traffic accidents, expenses to reduce maintenance and operating costs. However, most significantly as noted in the ASCE failure to act report by the EDRG (2013) attested that the bulk of the gap which is most affected by the surface transportation sectors comes from highway infrastructures assets needs, such as roads, bridges and transit systems. The implementation of asset management could play a crucial part in surface transportation life cycle by decreasing these foreseen financial, operational and legal risk associated with highway infrastructure conception, operation, maintenance and disposal.

Application of asset management could also assist in tracking the performance of surface transport infrastructure and improving the transparency of decisions making outcomes. Deteriorated highway infrastructure affects surface infrastructure systems, leading to high maintenance and transportation-related cost. Highway transportation cost plays a large part in surface transportation, and inadequate maintenance of the road asset affect businesses, households relying on the transport sector on a daily basis. Defect stands for deterioration from the expected performance condition, preventing an asset from functioning as designed. The UK road boards well-maintained highways Code of Practice defines defect in two categories. Those that represent an immediate hazard or short-term deterioration risk as Category (CAT) 1 while the CAT 2 defects are all other defects not considered to represent an immediate or impending hazard or possible short-term deterioration (UK Roads Board, 2005).

1.3 RESEARCH AIM AND OBJECTIVES

The drive of the research is to evaluate and develop applicable methods that could aid strategies for asset management and maintenance of highway assets and systems in Nigeria. The methods proposed should bridge the gap between highway asset management and maintenance of fielded systems with regards reliability, availability, maintainability and safety. The study has the following goals listed below for succeeding its aim.

i. To schedule preventive maintenance strategies for newly created highway infrastructure in Nigeria, using standardised maintenance information obtained from UK highway asset dataset via the application of an improved technique named reliability centred maintenance

ii. The reclassification of category 2 defect repair response time via the mitigation of hazard from highway assets defects using risk-based inspection and stochastic assessment.

iii. To investigate reliability indices for carraigeway failure events via means of graphical reliability growth analysis using the United Kingdom carraigeway fielded system to gain understanding towards possible application in Nigeria

iv. To institute transition deterioration and median life prediction models using carraigeway data set in lieu of supporting management decision making towards asset degradation prediction

v. To appraise an optimised cost implication technique using a treatment transition analysis method in bringing failed carraigeway assets back to a state as good as new.

1.4 RESEARCH METHODOLOGY

The strategy used in research is vital for its overall success (Royce et al., 2010). In accomplishing the objectives set out for this research, the inductive research method was adopted. The combination of qualitative and quantitative data types delivers an enhanced overall assessment of the asset management system and asset performance than dependence of only one measure (IAM, 2008b). The beginning phase of this research is to explore the literary context of maintenance, management of highway infrastructure assets and the effect/consequences of the unavailability of keys highway assets. Asset management features, principles and its benefits to highway infrastructure was investigated to give a better understanding of the research gap in highway infrastructures asset management, maintenance, and life expectancies. It is pertinent to note that two principal sources were introduced in the research study. Data on failure and maintenance history were extracted from the NMMS generated via Detailed Visual Inspection (DVI) and data of carriageway condition from SCANNER survey generated via a high-speed surface condition vehicle, both United Kingdom road authority dataset. The data sets are owned and kept by the surface transport directorate of the Transport for London (TfL).

A qualitative analysis was conducted using Case-Based Reasoning (CBR) method, a problem-solving methodology using the 4R'S (retrieve, reuse, revise and retain) was conducted with highway maintenance experts administering highway maintenance in the UK. The approach was insightful into failure types, ways of failures and maintenance strategies for the highway assets to support newly created fielded highway infrastructure. The investigation focused on capturing functional failures during their operating context using the method named classic Reliability Centred Maintenance (RCM). Functional failure is the inability of a system to meet a specified performance standard which includes the inability to function at the level of performance that has been specified as satisfactory. This RCM technique was based on an FMEA embedded in a decision logic tree and criticality analysis to enable recommendation of maintenance task and strategies. Even though the RCM technique achieved the maintenance interventions predictions for the newly created highway assets (a recently completed road junction network, in Niger Delta in Nigeria) via Failure Mode Effect and Criticality Analysis

(FMECA), quantitative judgements on the Mean Time To Failure (MTTF) and Mean Time Between Failure (MTBF) was not captured as RCM is more of a qualitative approach. Thus, a quantitative analysis of the failure event investigation is considered.

A risk-based quantitative analysis approach named stochastically risk-based inspection method is introduced to aid the investigation of Mean Time to Repair (MTTR) of CAT 2 defects. The joint evaluation of the Risk-Based Inspection (RBI) – Stochastic (STOC) approach helped in the reclassification of CAT 2 defect repair response time. The case study of this approach was conducted using real-time fielded highway systems datasets obtained from the UK, TfL Network Maintenance Management System (NMMS) for the period of 2010 – 2015. The NMMS model's five functional areas as listed below. (i) Fault Management—Detect, isolate, notify, and correct faults encountered in the network. (ii) Configuration Management—Configuration aspects of network devices such as configuration file management, inventory management, and software management. (iii) Performance Management—Monitor and measure various aspects of performance so that overall performance can be maintained at an acceptable level. (iv) Security Management—Provide access to network devices and corporate resources to authorized individuals. (v) Accounting Management—Usage information of network resources. The information in the dataset cut across all the highway assets and systems discussed in the RCM analysis. A bootstrap sampling of best-fit distribution was introduced to determine the best resultant stochastic interval against the standard repair response time.

The NMMS dataset was further introduced in reliability growth modelling using statistical assessment to generate parametric estimates, distributions, and growth curves. Graphical statistics, reliability analysis and reliability growth assessment were generated to help evaluate the failure time of events. Both analyses (the RBI and the RGA method) was conducted using real-time carriageway highway fielded data set obtained from the UK, TfL NMMS for the period of 2010 - 2015. The information input used in recording the failure events aligns with the standard NMMS as portrayed in the sample event input in Table 1.6. Having delved into the areas of FMECA using RCM, RBI with stochastic attribution and graphical RGA demonstration, the understanding of asset deterioration and costing was essential.

Table 1-6 Typical NMMS Data Entry Example from DfT UK NMMS system

N	**Field Inspection**	**Failure Data Entry**
1	Defect identification	000001
2	Defect borough	Greenwich
3	Road	Maritime way
4	Defect location	Maritime rd junction intersection
5	Defect description	Damage to sections of pedestrian guardrail
6	Defect category	1A
7	Activity code	FB - Safety Fences
8	Defect code	ACCD - Accident
9	Repair description	Cut, remove and replace damaged sections
10	Repair type	Temporary
11	Date inspected	01-JAN-2016
12	Defect period (Hrs)	0
13	Expected repair due date	28-JAN-2016
14	Repair period hrs/mins	13 Days
15	Date repaired	13-JAN-2016
16	Interval meaning	24 Hours
17	Estimated repair Cost	£100
18	Actual repair Cost	£78.72
19	Asset identification	000001
20	Asset end date	08-Nov-2016
21	Square meter area	NULL
22	Number / Impact	NULL
23	Treatment code	RRS
24	Treatment descr	Remove & reinstate surface
25	ML Flag	Maintenance

Source: (Network Maintenance Management System (NMMS) Dataset TfL UK)

A quantitative Markovian chain model that uses probabilistic and matrix operation is considered since it gives insight into the sequence of possible deterioration events. The Markov model approach in which the probability of future states depends only on previous states was instigated using inspection data generated from the carriageway asset condition survey of the United Kingdom Pavement Management System (UKPMS). A current state condition and a start-up transition in the form of Linear Transition Probability (LTP) is developed from the real-time carriageway condition data collected from the UKPMS SCANNER survey for the year 2013 and 2014. The Markovian chain model was after that used in predicting the sequence of states the assets could be in future years under no maintenance. This Markovian chain methodology was further extended using a strategic cost approach validation. The validation using analytic cost formulation is generated from the proposed treatment cost estimate taking into consideration the treatment transition towards developing the future state cost, which was based on the desired maintenance levels anticipated. As stated by Saunders et al., (2011), the inductive approach migrates from data to theory with a focus on generating new ideas which evolve after the data was utilised. The research is classed as inductive research because it migrated from the mixture of objective, subjective, quantitative, and qualitative analysis to philosophy.

1.5 RESEARCH MOTIVATION

The drive for highway infrastructure maintenance is to ensure the continuous availability of highway asset during operating times as well as exceeding the life expectancy of the assets. This PhD research is designed to capture knowledge which would have been lost due to the soon stepping down of present road maintenance specialists, taking into an acknowledgement that youths do not recognise the road maintenance industry to be dazzling (Belgian Maintenance Association, 2013; Orugbo, 2013). The significance of this study thus considers the application of risk and reliability-based maintenance approach that can uphold highway asset by application relevant methodology. The consequence of functional failure, defects, deterioration, and no maintenance of highway asset infrastructure as revealed in the failed road junction network in Figure 1.1 which consists of multifaceted highway assets in Niger Delta, Nigeria has aroused the researcher’s interest. The impact of the research study will improve the manner at which the maintenance and management of these multifaceted highway assets are envisaged.

The assets management approach, the assets worth, their service levels and future maintenance programme can be realised from the research. The techniques introduced in the study will enable an asset management approach where a maximum useful life can be gained from an asset found to have repeated short life repairs. The asset management method allows it to continue to a point where the deteriorated asset is no longer maintainable and needs reconstruction. The key reason for the research study is to enable asset owners to know the assets in their network well and weighing up all maintenance alternatives, which is a key to asset management success. The study makes available the efficiency of managing and maintaining the highway assets and what options are available which are unique to every individual type of highway asset. The study which entails the maintenance management systems of highway assets will allow using the condition information to ascertain need, when and how much maintenance is needed.

Research reports by ERA-NET (2010) and Audit Scotland (2011) as depicted by Orugbo (2013) on the systematic outsourcing and prioritization approaches for trunk road network maintenance and renewal process indicates that existing highway assets network maintenance strategies and standards have failed to deliver expected levels of service on Nigeria road networks. Inadequacies of existing highway asset maintenance strategies and standards exacerbate the impact of recent up comings such as growing road maintenance backlogs and a higher incidence of highway asset defects.

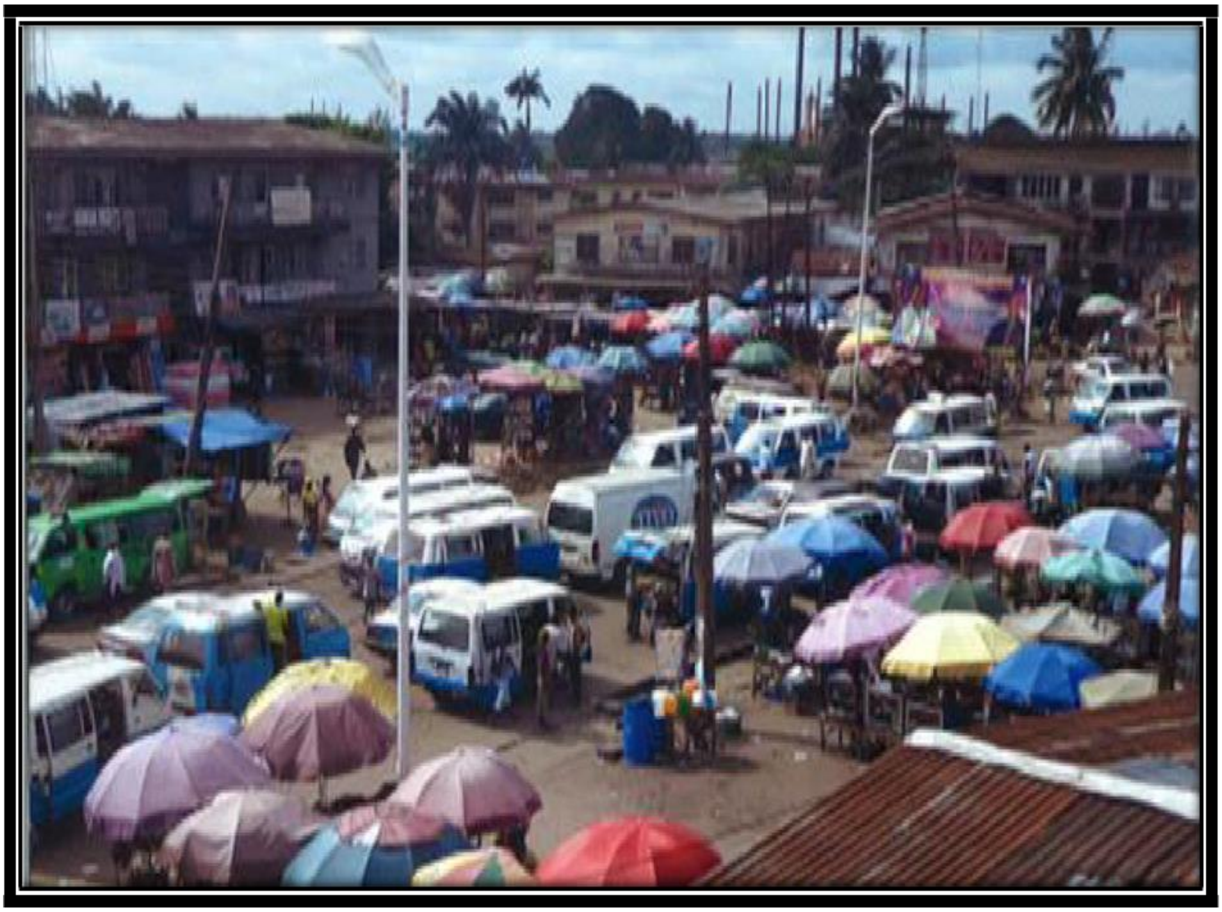

Figure 1-1 Failed Road Junction Network in Niger Delta, Nigeria

Source: (A.I.L Infrastructure Limited, 2013; Ekpiwhre and Tee, 2015, 2016b)

1.6 OUTLINE OF REPORT

The research consists of eight chapters and each chapter entails of the following as outlined:

CHAPTER 1 - This chapter presents the background of the research and highlights the importance of highway infrastructure asset management. It buttresses the importance of well-maintained road networks to a nation's economy and quality of life. Challenges of highway infrastructure maintenance and the effect of degrading infrastructure cost to the economy were discussed. The research aim and objectives, the methodologies and research significance and motivation, were deliberated.

CHAPTER 2 - This chapter describes literature and existing available research works in highway infrastructure maintenance, giving theoretical insights into strategies for highway infrastructure maintenance. The chapter describes the highway asset management framework and the approaches to highway assets management. The technique of modelling of a physical asset, their condition and performance metrics were discussed. The chapter concludes with strategies for decision making in asset management of physical structures.

CHAPTER 3 - This chapter presents an RCM strategy using CBR technique for highway infrastructure functional failures in the UK. The result of this chapter proposes appropriate maintenance strategies and tasks for addressing the functional failure of assets newly created highway assets in Nigeria. It began with a summary of RCM theories and previous applications of the techniques in various industries. The different stages of the classic RCM application were discussed and illustrated by the use of ten key highway assets. Results from the FMEA and criticality analysis application are presented and discussed.

CHAPTER 4 - This chapter presents a study piloted on highway assets Category 2 defects. A combination of RBI and stochastic (STOC) techniques are introduced in the analysis to give an in-depth understanding of highway asset maintenance actual MTTR as against the standard repair response time for Category 2 defects. Safety inspections piloted within 2010 and 2015 are evaluated using the projected RBI-STOC approach, and a reclassification of defect repair response in equivalence with a system MTTR are projected for consideration of reclassification of Category 2 defects response timings.

CHAPTER 5 – This chapter presents the application of reliability analysis and growth curves for modelling failure times and events. The reliability behaviour (MTTF & MTBF) of the carriageway fielded sample (carriageway) is evaluated using reliability estimates. The growth trend and parametric growth curves of the HPP and NHPP power law are presented using

Maximum Likelihood Estimation and Least Square Estimation as well as their computed Mean Cumulative Function (MCF) of failure times of events.

CHAPTER 6 - This chapter presents the Markov Chain model to determine highway assets current condition, modelling its deterioration and predicting future conditional states of the assets. The theory around the Markov Chain model and application of the Markov model were first discussed and afterwards the worked case study generated from carriageway asset condition data presented. The data study depicts the formulation of the carriageway assets current condition and probability transitions matrix developed and result validation presented.

CHAPTER 7 – This chapter is a trail up of Chapter 6, initiating currents state condition band develop for cost estimation projections. The procedure uses a five-point condition band in developing its ten prospective strategies for an analytic cost selection and optimisation. The revolution of the strategic model was presented in the similitude of picturesque and the outcome via an exploratory data analysis. The approach depicts the scenarios that each repair level action can have on the assets future performance and upcoming asset maintenance. The selection of an ideal price to renew the system to an optimal steady state was projected by considering the various cost scenarios and strategies.

CHAPTER 8 - This chapter entails a discussion on a sustainable highway asset and infrastructure management stating the contributions the research presented. The conclusions and limitation from the application of the method applied in the research are discussed. The recommendations and future works provide a suggestion that could support highway asset managers and create openings for further research with concerns with the maintenance of highway infrastructure.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

The asset management disciple has gained importance because of the value of money it provides an organisation that has embedded its principles. Organisations have recorded benefits regarding the increased availability of their asset, better system safety, increased asset lifetime, reduced life-cycle cost and compliance with legislation. Operating and managing asset throughout its entire lives cycle requires an appropriate AM approach to guarantee suitable returns as well as safety and service standards (Remenyte-Prescott and Andrews, 2013). The assets management discipline gives guidance on the operational performance and cost-effectiveness of establishments that operate assets in line with its frameworks (IAM 2008b). The IAM (2008a) relates the discipline of AM to be one that requires a framework to enable an organisation to optimise and implement the delivery of the organisation strategic decisions on the acquisition and management of its assets. AM frameworks are the best way of carrying out its operation, maintenance, inspection, revitalisation, improvement and disposal of physical assets to deliver a safe and economical transport system.

In a review of AM methods for networked systems, there are three key reasons why the increase of AM has been attractive within recent times, which are namely the ageing of systems, availability computerised database and structure changes with relation to industries (Brint et al., 2009; Remenyte-Prescott and Andrews, 2013). In buttressing the three critical reasons of AM recent consideration, Brint et al., (2009) stated that ageing of systems rapidly results from the longer use assets been put through, which is often far above their service life. The extensive use of assets would require a sophisticated maintenance strategy to improve such systems. Secondly, the institution of the high-tech data-based system is currently replacing paper-oriented registers, giving asset managers the opportunity and ability to generate better results and asset performance predictions from access to technologies for measuring the conditions of the asset. Finally, the changes in structures in operation and compliance in the industry where organisation are now compelled to submit AM plans as part of their periodic reviews to regulators of the industries they operate have led to the growth of the AM discipline.

2.2 FRAMEWORK FOR ASSET MANAGEMENT

AM usually takes a whole life-cycle cost approach to decisions regarding operation, maintenance, and replacement of assets. There are usually some maintenance strategies that can be applied to an asset to retain or restore its state needed to deliver a required level of service. Each approach leads to varying maintenance costs and asset availability. Hence, knowing the necessity of an asset management system is very crucial in developing the structure of an asset management framework for any organisation. Figure 2.1 gives an insight into a generic highway asset management framework by the County Surveyors Society (2004) for use in the UK.

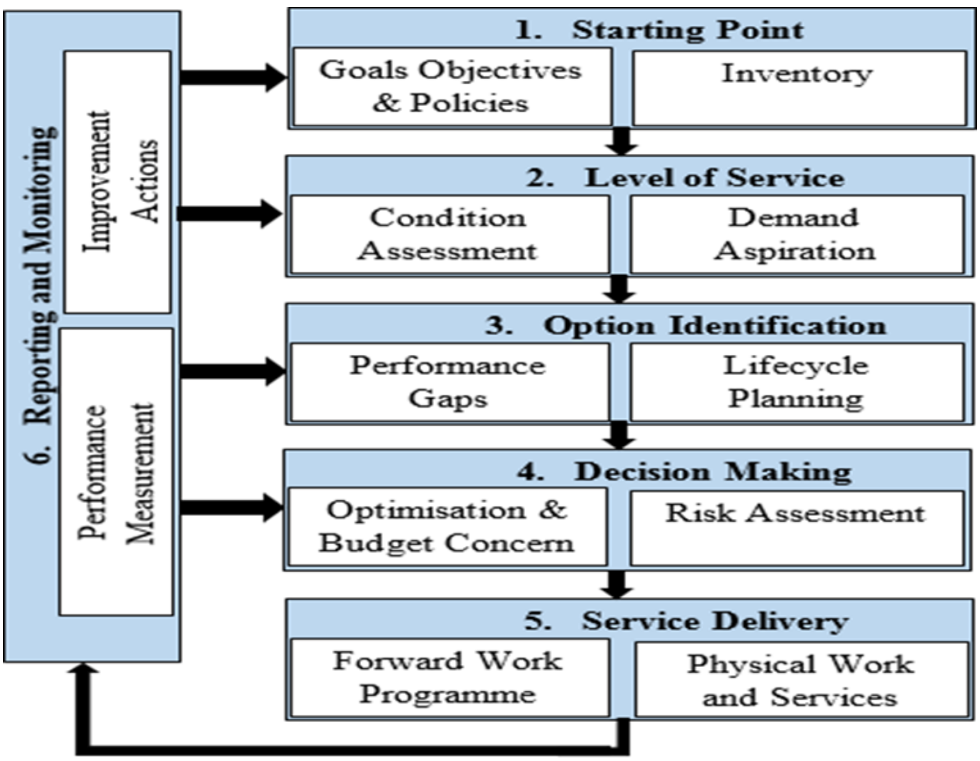

Figure 2-1 Generic Highway Asset Management Framework

Source: (County Surveyors Society, 2004)

Aiming to attain the highest level of service with the lowest expenditure is complex and requires an in-depth understanding of the asset performance condition, the maintenance alternatives, risks and cost at the various stages of the asset whole life cycle (IAM, 2008a). Dependencies between components in the network require a stable level of asset and its management because of the additional complexity that comes in consideration of the many different assets. Frameworks help illustrate how the various activates of the AMS framework (goals, objectives and policies, condition assessment, performance gaps, optimisation and budget and programmed works) are linked.

2.2.1 Asset Management Approach

The formal approach to AM are currently implemented in countries like the United Kingdom, the United States and New Zealand, but mostly applied in Australia. Unlike New Zealand, whose government energy sector has benefited from the implementation and use of asset management, the United State has applied AM majorly in its highway management and transportation plans. At the outset, sectors with massive physical infrastructure have shown more interest for AM in the United Kingdom (i.e., water, electricity distribution, oil and gas industry) but the highway sector is currently embedding itself with the AM principles in all its local council authorities (Adeney et al., 2006). Conferring to the framework specified by the Institute of Asset Management, AM is defined as;

''Systematic and coordinated activities and practices through which an organisation optimally and sustainably manages its assets and assets systems, their association performance, risks and expenditure over their life cycles for the purpose of achieving its organisational strategic plan'' (IAM, 2008: p.V).

The approach of AM aids efficient implementation which entails a disciplined attitude to enable the management of assets over their lifecycle to be achieved by organisations. The benefits attributed with the application of the AM approach includes health, safety and environmental improvement, optimised return on investment, best value for money demonstration and most importantly the ability to demonstrate that sustainable development is actively considered within the management of assets over their lifecycle (IAM, 2008a). The IAM asset management application process as presented in Figure 2.2 commences from discrete components whole life cycle optimisation (create, utilise, maintain and disposal), a sustained performance cost and risk for the asset management system, and a capitalised investment optimisation and sustainability planning for the asset management portfolio.

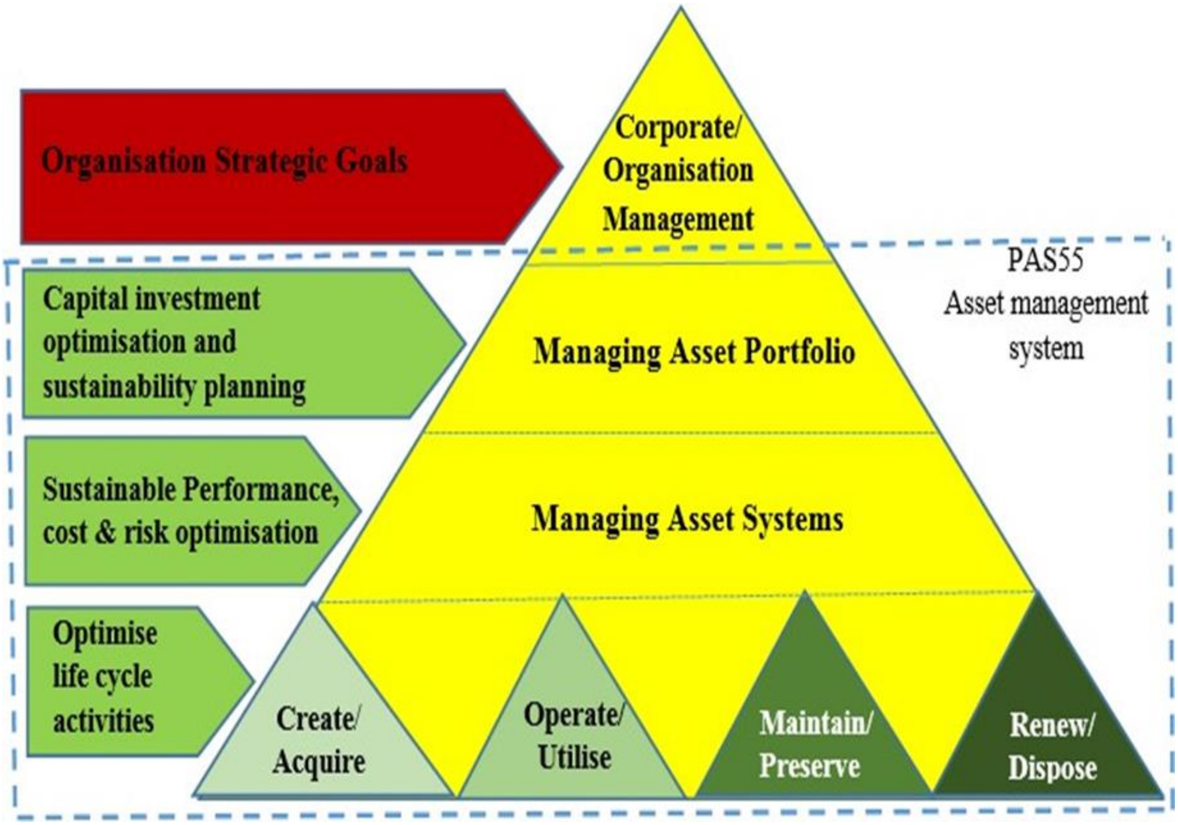

Figure 2-2 Assets Level and their Management

Source: (Institute of Asset Management, 2008b)

It is necessary for an AMS to be considered for all assets of the highway's networks. AM has the capability to serve the requirements of all its constituents associated with its systems and should attempt to combine all kinds of inspection and monitoring types, a collection of data and a robust decision support system (Remenyte-Prescott and Andrews, 2013). Figure 2.2 illustrates the asset level and their management, portraying the concerns and priorities of the various standard of the management of physical asset systems which comprises the blend of cost, risk and performance. How the corporate management of the organisation is set up and the procedure from asset creation to the disposal of the asset after the lifetime or replacement in entailed for a good understanding of the various asset level and their management.

A variety of organisations has benefited from the application of assets management, the U.S EPA and Federal Highway Administration conducted a multisector asset management case studies which support the introduction of AM principles. The findings pointed out from the cases studied indicated that innovative AM methods offer established approaches to societies towards systems monitoring capabilities and advanced decisions support systems cutting across various service sectors (i.e., highways, wastewater, and airports) in the United States (U.S Environmental Protection Agency and U.S. Federal Highway Administration, 2013). According to the IAM PAS 55, AM policy, strategies, objectives and plans are founded on every organisation strategic plan, which in turn enables the diverse portfolio of AM to benefit from life circle activities applied towards them (IAM, 2008a). Successful application of AM in an organisation consists of the following (i.e., setting standards, assets records, identification of asset needs, prioritising maintenance needs, effective work programmes and outcomes, influencing maintenance via design, performance measurement and innovation and design).

2.2.2 Strategies for Asset Maintenance and Management

Some different maintenance strategies with the advent of new technologies can be used to maintain the state of the asset and the ageing of infrastructure systems (Brint et al., 2009). In general, maintenance activities can occur on asset failure, according to a schedule, asset condition or risk of asset failure (Tsai et al., 2011; Zhang and Gao, 2012; Gao and Zhang, 2013). Traditional maintenance practices have typically been dedicated to remedial action, however, to delay asset ageing and reduce failure costs, preventive maintenance is becoming more popular. Preventive maintenance approach is often kicked against considering the many constraints associated with it. Carrying out maintenance on busy transport infrastructure, for example, can involve many disturbances for travellers. Strategic and successful maintenance and management of assets, therefore, requires not only relevant data on asset condition to support scheduling maintenance activities but support condition-based maintenance. Approaches to system health monitoring are increasingly being used for AM as trends in a deteriorating condition of the asset can be obtained in real-time and maintenance actions can be planned in a window of opportunity before the failure occurs (Mustapha et al., 2014).

2.2.3 Multi-Component Maintenance Management

In consideration of multi-component maintenance forecast, two tactics for effective maintenance are utilised namely group maintenance and opportunistic maintenance. In group maintenance application, the components to be replaced or repaired are grouped. Whenever one of the components in a group fails, the whole group is maintained or replaced. In opportunistic maintenance, preventive and corrective maintenance activities are combined when certain economic and technical criteria are satisfied. These unplanned preventive maintenance actions are performed when the system stops due to a failure. Thus considerable savings in maintenance costs are projected, in addition to shorter service disruption times due to maintenance. Multi-component system monitoring and maintenance has been helpful in various industries and applications (Marseguerra et al., 2002). In the study of the general algorithm with prognosis information in system multi-component maintenance application by Camci (2009), the issue of categorisation of the dependence of components within a complex system is addressed. Elements of a complex system are identified which need to be addressed in network AM strategies into three groups. Firstly, functional dependence (a component stops when its dependent component stops), secondly, economic dependence (joint maintenance of dependent components saves the maintenance cost) and finally, stochastic dependence (effects of outside factors on all components). In conclusion, the report stated that when the asset is interdependent, the predicted time of failure of single components is not satisfactory for the best analysis.

2.3 ASSET CONDITION ASSESSMENT SYSTEM AND PROCESS

In the development of a performance evaluation tool towards asset condition assessment for sustainable AM, the process is assumed to rate asset with regards their condition considering a variety of factor (Abbot et al., 2007). The Department of Public Works, Queensland, Australia description of condition assessment states that it is any technical valuation of the physical state of an asset, using a systematic method to produce consistent, relevant and useful information (Queensland Government, 2012). Asset condition assessment often comprises physical inspections, real condition assessment; maintenance works identification and much more.

Condition assessment systems in very useful for assets managers. Zimmerman and Stivers (2007) in their report to the NCHRP on maintenance condition assessment systems, portrays that a condition assessment system that is enhanced can help report the current status of the asset and provide other uses as follows:

- Establishing performance targets;
- Setting maintenance priorities;
- Determining the funding needs to achieve;
- Deploying maintenance to failure events.

2.3.1 Condition Assessment Rating and Assessment Process

Rating of condition assessment system has been a challenge as there has not been a consistent, stable or firm way to assess asset performance condition. Thus, the use of rating systems is crucial to understanding the spreads of assets condition (Mc Dulling, 2006). However, condition rating has been used in literature and other studies (Zhang and Brani, 2005; Baik et al., 2006; Zimmerman and Stivers, 2007). The use of a five-point condition rating is assumed to be most effective than the others. A five-point scale proved to be most effective, as a three-point scale is presumed to be too coarse for reliable results, while a seven-point or more scale is too subtle and challenging for assessment staff to interpret consistently (Abbot et al., 2007). In the understanding of the points system which is still not very consistent within the built environment because of its subjective interpretations, Mc Dulling (2006) considers shortage depth that might arise from those coming from the medical, educational and financial sector. Hence it was considered beneficiary to introduce colour coding to condition rating systems as shown in Table 2.1 for user-friendliness boosting and quick understanding from those outside the field.

Table 2-1 Condition Rating with Colour Code

CAT	Condition	Required Action	Maintenance Description
1	Very Bad (VB)	Replacement	Not viable. Level of system failure does not justify rehabilitation or repairs as it has failed. The system is non-operational
2	Bad (B)	Rehabilitation	Major defect. Level of failure is substantially high as the significant part has failed
3	Fair (F)	Repairs	Average condition. Significant parts of the system, component or asset require repair
4	Good (G)	Condition Maintenance	Minor Defect. The asset has signs of wear and tear, minor defects that require maintenance
5	Very Good (VG)	Planned Preventive Maintenance	No defect. The component, system or asset are in their new state or recently maintained and shows no sign of defect or deterioration

Adapted: (Mc Dulling, 2006; Abbot et al., 2007; Queensland Government, 2012)

Drawing from Abbot et al., (2007) as shown in Table 2.2, the condition profile of any system been arbitrated to 100% per time would consist of various components of the systems in different condition and the possibility to change over time. With the consideration that the components of the systems change over time, different levels and type of maintenance would be required in line with the level of each components condition.

Table 2-2 Field Assessment of Condition Rating

Condition	**Very Good (VG)**	**Good (G)**	**Fair (F)**	**Bad (B)**	**Very Bad (VB)**	
Action Required	Planned Preventive Maintenance	Condition Maintenance	Major Repair	Restora tion	Replace	Cumu -late
Condition	5	4	3	2	1	
Assessment	A%	B%	C%	D%	E%	100%
Example	33%	27%	20%	13%	7%	100%
Example	0.33	0.27	0.20	0.13	0.7	1

Adapted: (Abbot et al., 2007)

2.3.2 Condition Assessment Applications

The importance of current and comparable condition assessment across a network group is of great value. With these attributes of forecasting, intervention plans could be easily decided due to information readily available (Eyre-Walker et al., 2014). Also to be noted from the report for NCHRP by Zimmerman and Stivers (2007) is the objective and subjective condition assessment information with consideration for use in assessing system proportions. An objective evaluation method is encouraged as objective condition information gives a fair result compared to a subjective condition assumption. The following are benefits that assets owners, authorities would gain using enhanced approaches to assess the condition of their assets. The transportation sector assets can take advantage of the utilisation of the condition assessment data in supporting their decisions. The availability of objective condition information provides a means of accomplishing the following:

- Establishing targeted condition levels for each asset within the available funding level;
- Improving links between customer expectations and maintenance activities
- Understanding the cost of changing asset conditions from between the level of service;
- Establishing consistent conditions across an entire highway system;
- Reassigning resources to under-performing assets;
- Setting maintenance priorities on a statewide basis.

2.4 INSPECTIONS AND SURVEYS

Highway infrastructure inspections and surveys can be revealed in various classifications, conforming to the goals of highway maintenance (UK Roads Board, 2005). The formation of an effective regime of inspection, survey and recording is the most crucial component of the maintenance of highway infrastructure. Highway inspections are carried out either by foot or by vehicle. Highway inspections carried out on foot are known as walked inspection while the vehicular inspection is called a driven inspection. Both inspection methods are often used interchangeably, but significant safety consideration is given by walked inspectors inspecting defects on the carriageway (Lancashire County Council, 2015). Inspection and surveys are considered into three main categories because of their objectives and functions namely, safety inspections, service inspection and condition surveys.

2.4.1 Safety Inspections

Safety inspections are aimed to detect all highway infrastructure defect possible of creating danger or severe inconvenience to users of the network. Safety inspections could be undertaking in slow vehicles or by walking. When carried out on the carriageway, the slow vehicle could be utilised, but such an approach may not be practical for the walkway because of pedestrians using the road, and a walked inspection would be recommended. The necessary parameters required for a safety inspection regime should consider inspection frequency, an asset for inspection, the degree of deficiency and the response nature require of such. The UK Roads Board (2005) in its Code of Practice states that safety inspection regimes should be developed based on risk assessment, taking into account road users. Safety inspections regimes form a key part an organisation approach to managing the risk and liability of their assets, having its regime developed on a risk-based assessment provides a practical and reasonable approach to the risk impact identified.

2.4.2 Service Inspections

Service Inspection is for thorough inspections which are personalised to the requirements of the highway infrastructure assets. The inspection comprises of a detailed assessment tailored to the requirement of the assets or element to ensure that they meet serviceability requirement. Maintenance of network availability, reliability and integrity for regulatory purposes are carried out by highway inspectors in a walked inspection approach and are focused on asset performing their function and meeting the needs of the users (UK Roads Liaison Group, 2016). The inspection is designed to ensure performance or regulatory purpose. Service inspection can also be carried out either individually on in conjunction with safety inspections, and the various types of service inspections can include Coarse Visual Inspection (CVI) or Detailed Visual Inspection (DVI) (Transport Research Laboratory, 2011).

2.4.2.1 Coarse Visual Inspection (CVI)

CVI is a coarse, rapid survey, usually carried out from a slow-moving vehicle that allows for the assessment of the left and right of the carriageway, foot/cycleway, and kerbs in the road network to be assessed yearly. The highway infrastructure best value performance can be known by this method.

2.4.2.2 Detailed Visual Inspection

This approach which is more sophisticated than the CVI identifies defects by a larger number of detailed classifications. Unlike the CVI which is conducted in a slow-moving vehicle, the DVI is a walked survey with a focus on previously identified length or area in need of maintenance either by CVI or other sources. DVI surveys can be used to produce best value performance indicators also but must first be converted to CVI similar data using appropriate software conversion mechanism. Road network where the driven survey is not possible can employ a DVI approach. This method is also advantageous to validate maintenance decisions and scheme identifications.

2.4.3 Condition Surveys

Condition surveys are principally intended to ascertain deficiencies on the highway infrastructure asset material which if untreated are sure to affect the life expectancy, performance and serviceability of the assets and systems. The UKPMS Condition Surveys uses various inspection methods for highway infrastructure namely SCANNER surveys, Sideway-force Coefficient Routine Investigation Machine (SCRIM), Deflectograph and machine measured rutting. Condition survey applications have relieved the highway authorities financially since its application came into use; even when its- applications are mostly for carriageways and pavements. Condition surveys have enabled asset owners to make a projected judgement on asset future, but most importantly it is the ability to make short and long-term plans from information generated by such surveys (UK Roads Board, 2005; Transport Research Laboratory, 2011).

2.4.3.1 SCANNER surveys

SCANNER surveys are used for the collection of data from the high-speed surface condition. SCANNER surveys have been developed to provide an objective and consistent approach for assessing the condition of all non-principal roads across England, UK. The SCANNER survey vehicle uses the accuracy of the 3-dimensional spatial coordinates of the road network to determine and collect information on its road geometry, longitudinal profile (LV), transverse profile, texture profile (LLTX), wheel path rutting (LLRD) and cracking (LTRC). This high-speed surface approach whose advantage is yet to be enjoyed by local road the is capable of developing the carriageway transverse profile edge condition and happens to be the most currently used condition survey type in the assessment of carriageway road condition (Transport Research Laboratory, 2011).

2.4.3.2 SCRIM

The measurement of the wet skidding resistance on the road network is the purpose of the creation of the SCRIM. The sideway-force coefficient is calculated from the relationship between the force generated by the resistance to sliding, the force created by the resistance to sliding and the wet skidding resistance. The method operates in a controlled wet road condition to enable for forwarding sliding in the direction of the wet road surface. The functional defects are the output produced by the SCRIM survey.

2.4.3.3 Deflectograph

The use of deflectographs measures the structural condition of the flexible composite pavement. The Deflectograph which is a self-contained lorry mounted system uses an automated deflection measuring system. Deflection at intervals of 4m in both wheel paths is generated while the machine is in a motion mode. Unlike the SCANNER survey which is prominent in England and used to determine surface condition, the deflectograph usage is most frequently used in Wales and Northern Island, UK, to monitor surface condition of the whole carriageway.

2.5 MAINTENANCE EVOLUTION AND PHILOSOPHY

Maintenance management techniques have been through a significant process of metamorphosis over recent years. Today, the maintenance progress has been provoked by the increase in complexity in manufacturing processes and a variety of products. The growing awareness of the impact of maintenance on the environment, safety of personnel and the profitability of the business and quality of products has brought about maintenance progression (Khan and Haddara, 2003). There is a paradigm shift in executing maintenance strategies like condition-based maintenance (CBM), to Reliability Centred Maintenance (RCM) and then the Risk-Based Maintenance (RBM) in the current generation (Orugbo, 2013). The development of maintenance philosophies presented in Figure 2.3 reveals how maintenance policies have evolved and can be categorised as first, second, third and recent generations.

Table 2-3 Maintenance Evolution and Philosophy

1st Generation 1940 -1950	2nd Generation 1950 -1980	3rd Generation 1980 - 2000	Recent Generation 2000 upwards
Fix it when broken Basic and routine maintenance Corrective maintenance	Planned preventive maintenance Time-based maintenance System for planning and controlling works	-Condition-based maintenance -Reliability centred maintenance -Computer aided Maintenance and management -Workforce multi-skilling and team working -Emphasis on Reliability and availability	-RBI, maintenance and life assessment -Reliability centred maintenance -Condition-based maintenance -Computer aided maintenance management and information system -Preventive maintenance optimisation

Adapted: (Nowlan and Heap, 1978; Adoghe, 2010; Orugbo, 2013)

Maintenance is defined as a set of actions taken to ensure that systems or components provide their intended functions when required with one of the primary objectives of restoring or preserving reliability at a minimum cost (U.S Navy Sea Systems, 2007). Then crucial focus for maintenance is preserving the intended function of the asset to ensure the availability of the function has been continued at all time. The aim of carrying out a maintenance programme is to address the unsatisfactory conditions in which intended functions are not adequately been provided, often called functional failure. It is believed that the short, medium and long-term strategies relating to the entire useful lifetime of an asset can be identified by a good maintenance management system which provides operators vital information and decision making support (Cheng et al., 2008). Maintenance activities can be categorised into preventive maintenance and corrective maintenance as well as other different types and strategies as described in Table 2.4 by the European Commission in a training handbook (Voyatzopoulos and European Commissions, 2012).

Preventive maintenance (PM), which is the focus of this study, is an upkeep programme with actions initiated at predetermined intermissions, or according to agreed standards, with the intention to decrease the probability of failure, or the dilapidation of the functioning of an asset. Some PM tasks have been introduced to depict the approaches of PM. However, It is underestimated not to acknowledge maintenance inspections with relation to PM. Highways infrastructure requires viable inspection regimes to enable highway engineers and asset managers not only strategies maintenance task and periods but also aids in appraising the current condition of assets and support decision makers with right information of the state of their asset and how to spread their funding.

Table 2-4 Maintenance Types and Strategies

MAINTENANCE TYPES		**STRATEGIES**
1	Condition-Based Maintenance	Maintenance based on performance and parameter monitoring and the subsequent actions
2	Corrective Maintenance	Maintenance carried out after fault recognition and intended to put an item into a state in which it can perform a required function
3	Deferred Maintenance	Maintenance which is not instantly carried out after a fault detection but is delayed by given maintenance rules
5	Online Maintenance	Maintenance performed during the time that the item is in use
6	Onsite Maintenance	Maintenance carried out at the location where the item is used
7	Operator Maintenance	Maintenance completed by a user or operator
10	Predictive Maintenance	Maintenance performed following a forecast derived from the analysis and evaluation of the significant parameters of the degradation of the item
11	Preventive Maintenance	Maintenance carried out at predetermined intervals or according to prescribed criteria and intended to reduce the probability of failure
12	Scheduled Maintenance	Maintenance carried out by an established schedule or established number of units of use
13	Cyclic Maintenance	Maintenance carried out at regular intervals
14	Routine Maintenance	This type of maintenance is carried out in a cyclic pattern
15	Reactive Maintenance	This type of maintenance refers to works that are carried out as a matter of urgency, usually for reasons of safety

Adapted: (Voyatzopoulos and European Commissions, 2012)

2.5.1 Preventive Maintenance (PM)

PM is designed to be conducted at intervals that are predetermined conferring to prescribed standards with intent to reduce the probability of failure or the degradation of the functioning of an item (Wu and Ming J.Zuo, 2010). It helps to minimise the opportunity for functions to fail through the use of tests, inspections, replacements and routine actions (U.S Navy Sea Systems, 2007). The probability of failure can be determined for an individual system or asset and component which could be replaced or repaired in time to avoid functional failure. For example, the lamp of the lighting system is replaced after a period as the failure rate increases with time in use. With the advancement of maintenance methodologies, the different asset failure characteristics are addressed by use of PM strategies periodicities such as Time-Based Maintenance (TBM) or CBM.

In designing periodic PM policy, an asset is preventively maintained at planned time intervals nevertheless of the failure history of the asset and repaired at intervening failures. Periodicity could be in block replacement in pre-arranged times for components or periodic replacement at predetermined intervals to enable early detection of failure and elimination by minimal repair (Sarkar, Subhash and Sarkar, 2011). In the maintenance analysis by Smith and Mobley (2008) and Smith (2015), the optimisation of the inspection periodicity of the PM activities via investigating asset reliability enables the asset owners to set the PM periodicity based on finding retrieved from its analysis. The periodicity indicates how frequently the maintenance activity is to be conducted. Knowledge of failure pattern of the asset is necessary prior forecasting maintenance task period. The failure pattern information can help ensure the predicted functional failure does not occur in between maintenance period taking into consideration that periodicity is often calendared or non-calendar based.

2.5.1.1 Time-Based Maintenance (TBM)

Time-Based a PM method carried out in established intervals of a schedule or some units of use without previous condition investigation. Its maintenance task restores an asset back to its actual condition before it reaches a stage where the probability of failure becomes high and is the most suitable for addressing age-related failures. The TBM involves creating a maintenance regime where maintenance tasks are in time-based patterns usually hourly, daily, weekly, monthly, or yearly. It is assumed that time directed (TD) maintenance periodicity approaches are costly because the useful life of the asset is often giving up since the maintenance is not based on asset condition but calendar period (Berneski, 2014). All assets have worn out stage within their whole life cycle when they reach a point where there is a marked increase in the conditional probability of failure of the asset or subsystems. Failure modes of the asset are essential in making decisions for the TD approach. TD tasks are appropriate if the basis that the wear out typically is well-known for the asset involved (Nicholas, 2004). In the utilisation of the TD approach, the reliability of asset is plotted against time for the failure mode. A scalar parameter lower than one indicates a decrease in failure rate whereas above one indicates an increase in failure (ReliaSoft Corporation, 2015).

2.5.1.2 Condition-Based Maintenance (CBM)

Condition-Based Maintenance is a PM method carried out based on monitoring the performance or parameters of the asset. CBM is used to discover a potential failure to enable a correction to be realised thereby avoiding the occurrence of the potential failure. Inspections or conditional monitoring systems are attributes of Condition Directed (CD) tasks which are often used to maintain non-age-related failures (Besnard et al., 2010). Early detection of failure and degradation of assets has increased the use of the condition-based approach to maintenance. The use of a condition-based approach has become possible and consistent due to the availability of predictive technologies and methods to detect the need for corrective actions (Nicholas, 2004). CBM tasks (i.e., vibration analysis, wear particle analysis, ultrasonic flaw detection, and visual inspection) are periodic tests or inspections.

CBM is used to equate the asset current conditions or performance of the asset with established standards to determine the need for a follow-on repair, restoration or renewal and to avert the functional failure of an asset arising. The approach is viable if the failure mode characteristics are detectable with the adequate and consistent period amongst potential failure (P) and the occurrence of the actual failure (F) known as the (P-F) interval as shown in the P-F curve in Figure 2.3. The P-F curve as presented in Figure 2.3 uses the graph to demonstrate the connection between functional failure and the potential failure (Asset Insights, 2013). However, it is practically challenging to determine a 100% confidence from detecting a failure from inspection (Berneski, 2014). The number of inspection is vital in determining the periodicity of maintenance interval, but it can be assumed that the higher number of inspection gives higher confidence of detecting a potential failure at an earlier stage.

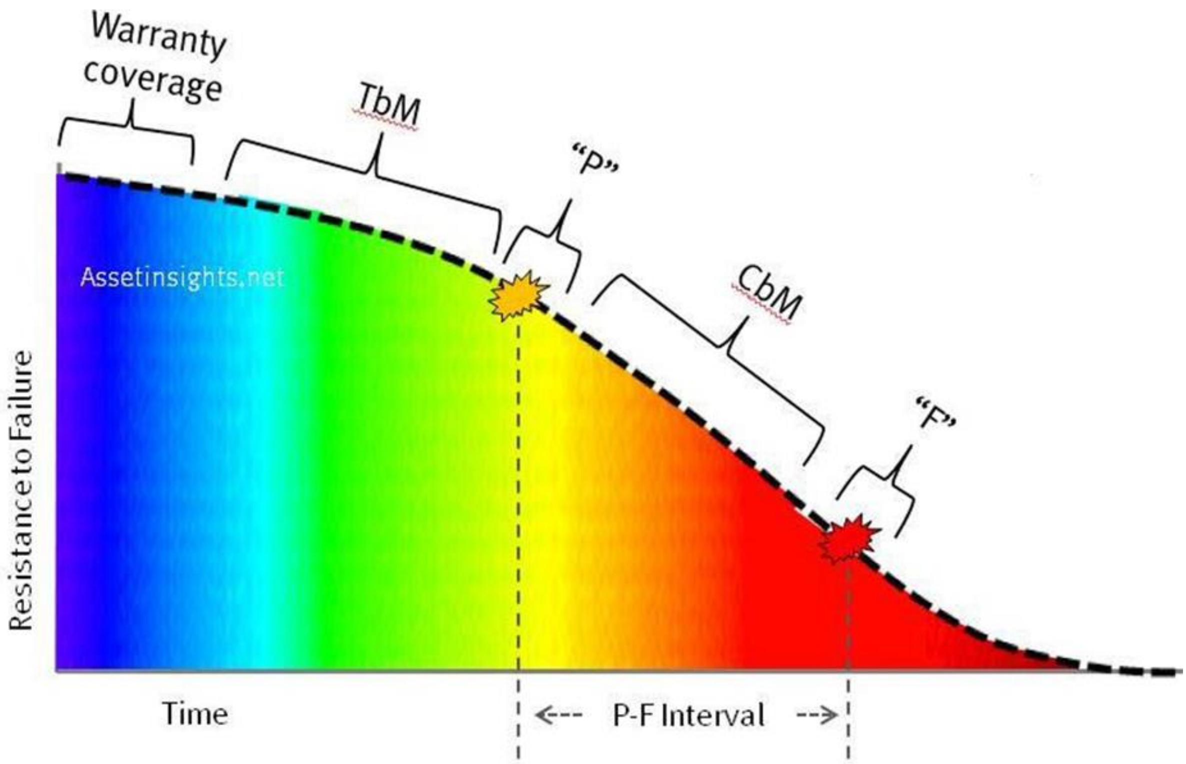

Figure 2-3 Potential Failure –Functional Failure (P-F) Curve

Source: (Asset Insights, 2013)

2.6 RISK-BASED ASSET MANAGEMENT

Lack of planned inspection and maintenance can turn new or existing highway systems and assets of a road network into a death trap or environmentally degenerated area. Deprived inspection of fielded highway infrastructure on a road network would have a fast rate value depreciation. A report for TfL depicts that the intervals for inspections for highway assets are principally the same notwithstanding their strategic importance and risk of failure (Atkins, 2011). These inspection interval standards and strategies are not designed to cater for low-risk defects on assets. Since reasonable regulation is currently unavailable, flexibility in regimes of inspections and maintenance practice that can alter the inspection intervals, based on risk estimation is often desirable. Inspection regimes could be altered in recognition of an RBI approach. Inspections, surveys and assessment regimes are often used to address highway maintenance core objectives with concerns to safety, serviceability and sustainability of the road network been a critical part of HAMP development. A highway risk management review by Gallagher Bassett (2011) reports that deficiencies due to defects on the road network which causes approximately 5 million incidents on a yearly basis, with maintenance related defect estimated to be 95% and design defect 5%.

Structural failure defects are a paramount consideration from any inspection and maintenance approach. The importance of inspection and maintenance for system and assets of civil engineering infrastructures is of high priority as the failure and depreciation consequences could be fatal, severe and very costly (Tee and Li, 2011). The UK Roads Board (2005) published a Code of Practice for highway maintenance management entitled the well-maintained highways. This new code replaced the first Code of Practice which published in 1983. The requirements set by the code are to help highway authorities in addressing the problems relating to the increasing growth in traffic. Highway maintenance is in need of risk management approaches because of the possibility of life-threatening events that can occur and lead to highway system failure arising from assets with a low likelihood of occurrence (Dicdican et al., 2004). There is a growing need for methodologies that can support recognised and formal AM of highway structures. Highway structures until recent times have been assured by design, assessment and maintenance of standards and regular inspections to ensure that anticipated deterioration or accidental damages have not occurred (Atkins, 2011).

Risk management is a core requirement for achieving an optimised AMS, and it is currently frequently used for physical asset assessment (Tee and Khan, 2012). Traditional methods of risk analysis on highway structures mostly consider risk implicitly and not in a manner auditable, thus leading to the obfuscation of high-risk or low-risk assets for management purposes. Risk-based probabilistic methods reveal multi-level interactions between risk parameter with the ability to quantify their variabilities. A risk-based factorial probabilistic inference was introduced to optimise control systems which led to the realisation of system cost variability and multi-level risk parameter (Wang and Huang, 2015). Several industries have welcomed the importance of risk-based tactics as an instrument for inspection planning and maintenance of components or assets carrying the highest risk (Atkins, 2011; Washer et al., 2016). RBI and maintenance methodologies have been developed from time-based through condition- based as shown in Figure 2.4 (Atkins, 2011; American Petroleum Institute, 2002). Well established standards and good practices for the application of systematic risk analysis for systems inspection and mitigation planning have been applied successfully in various sector extensively.

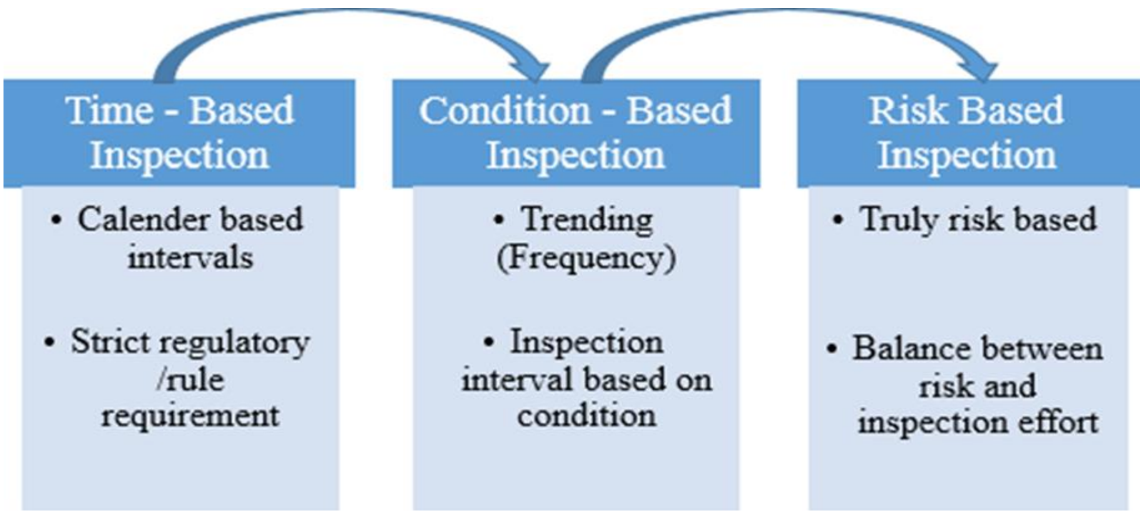

Figure 2-4 Inspection and Maintenance Strategy Progression

Adapted: (Atkins, 2011)

2.7 RELIABILITY GROWTH

Reliability of a system or component is defined as its ability to fulfil its design functions under designated operating and environmental conditions for a specified period. Reliability is therefore mathematically defined as the probability of occurrence of the corresponding event of failure. Although the literature focuses on the reliability growth of repairable systems, non-repairable and their lifetime distribution models cannot be ignored as they make up a crucial part of road infrastructure systems. The non-repairable populations as defined by Natrella (2010), are those specific items which are removed permanently after failing functionally. The systems are repaired by replacing the failed units from either a similar or a different population.

Reliability analysis deals with failure time (i.e., lifetime, time-to-event) data. For example, t = time from start of product service until failure or time until a warranty claim or a number of hours in use/cycles until failure. We call t a lifetime random variable if it measures the time to an "event"; e.g., failure, death, eradication of some defect/condition, etc. To describe reliability fallout a probability model that describes the fraction fallout over time is needed. This is known as the life distribution model. Engineers are often involved with reliability studies because reliability is strongly related to product quality. There are many well-known lifetime distributions, including exponential Weibull Gamma, lognormal, inverse Gaussian, Extreme value, log-logistic, etc. Lifetime distribution models are the theoretical population models used to describe non-repairable systems lifetimes.

Lifetime distribution models can be any probability distribution function (*pdf*) f (t) defined over the range of time from t = 0 to t=∞. The corresponding cumulative distribution function (*cdf*) *F (t)* is a very useful function, as it gives the probability that a randomly selected unit will fail by time *t*. Figure 5.2 below shows the relationship between *f (t)* and *F (t)* and gives three descriptions of *F (t)* (Natrella, 2010).

1. F (t) = the area under the *pdf* f (t) to the left of *t*.

2. F (t) = the probability that a single randomly chosen new unit will fail by time *t*.

3. F (t) = the proportion of the entire population that fails by time *t*.

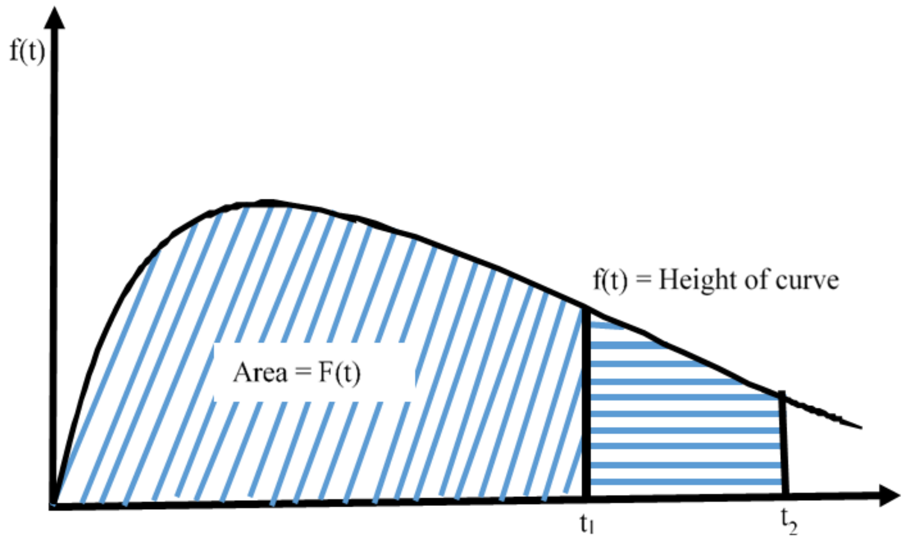

Figure 2-5 Relationship between *f (t), F (t)* and other *cdf* description

The figure above also shows a shaded area under f (t) between the two times t1 and t2. This area is *[F (t2) −F (t1)]* and represents the proportion of the population that fails between times t1 and t2 (or the probability that a brand new randomly chosen unit will survive to time t1 but fail before time t2). The *pdf f (t)* has only non-negative values and eventually either becomes 0 as t increases or decreases towards 0. The *cdf F (t)* is monotonically increasing and goes from 0 to 1 as t approaches infinity. In other words, the total area under the curve is always 1.

A repairable system as defined by Ascher and Feingold (1984), is a system which after failing to perform one or more of its functions satisfactory can be restored to entirely satisfactory performance (Fang et al., 2014). The restoration can be by ways and means other than replacement of the whole system. Conventionally, the literature on repairable systems is delved towards modelling of failure times using point estimations as presented in many applications such as maintenance optimisation actions by (Khan and Tee, 2016), whole life cycle costing by (Tee et al., 2014), decision making by (Zhang et al., 2016); (Zhang et al., 2016) and system reliability by (Li et al., 2016); (Tee and Khan, 2014). Repairable systems are classified into three categories namely minimal repair, normal repair and perfect repair basing the outcome on its repair level.

Consequently, these repair models are categorised based on their failure intensity to time, with the HPP models, a known renewing process model having a constant failure intensity. The NHPP models, whose proportional intensity model has one of the most favourable approaches has a time-dependent failure intensity (Cox, 1972). The NHPP model is stated by Ascher and Feingold (1984), as the fundamental models for realistic modelling of repairable systems. The General RP model representing the normal also called partial repair is intertwined with the proportional intensity and proportional hazard qualities. The organisation chart in Figure 2.6 portrays the fundamental relationship between established classes of models and their dependence on failure intensities. In this analysis, we will consider modelling reliability growth for the improvement of repairable road pavement systems.

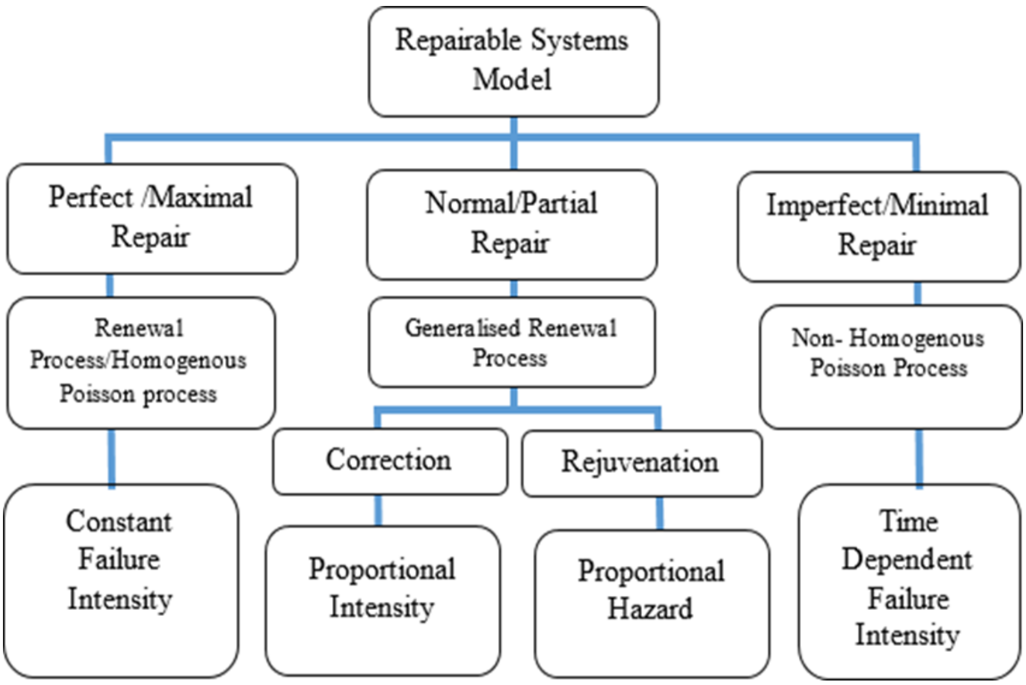

Figure 2-6 Failure Intensity Relationship between Models of Repairable Systems

Adapted: (Percy and Alkali, 2007)

Reliability improvement test for reliability growth modelling entails test procedures aimed at determining and fixing causes of system unreliability, with a focus on design and assembly of the structure as well as its failure causes. Even though a repairable system, having no improvement or degradation trend, can only be modelled by the HPP model, there are several models capable of describing a system with a decreasing repair rate (reliability growth patterns). Fortunately, models such as HPP and NHPP exponential law have been successful in a wide range of industrial application available in the literature. The introduction of reliability growth approach to system designs as seen benefits such as warranty and replacement cost minimisation, safety and satisfaction of service users, delivery cost reduction and supporting organisation profitability and competitiveness. Although the models of L.H, Crow, Crow (1974) and J.T Duane, Duane (1964) are most frequent in Reliability Growth Analysis (RGA)., T.P Wright, Wright (1936) and Davis (1952) were amongst the foremost in proposing the idea that improvements times can be represented mathematically. Findings from Wright (1936) showed that as the number of aeroplanes produced in sequence increases, the direct labour output decreases and its result is a straight line when plotted on a log-log paper. Davis (1952) summarised the rationale and statistical techniques using exponential theories of failures.

Failure data analysis was introduced to various samples obtained from operations performed by machines (Bus motor failure, incandescent lamp failure) and people (Payroll check error, student typing error). The Duane model by J.T Duane, a very projecting model for reliability and survival analysis noted a straight line in the successive cumulative estimates of MTBF versus the cumulative operating time when plotted on log paper (Duane, 1964). Further study of the Duane model, Crow (1974) observed that the process of Duane model could be computed as a Weibull process, making it possible to be utilised for reliability growth modelling, thus giving the extension to the Crow-AMSAA model, an NHPP process. The prominent relationship between both Duane and Crow-AMSAA model is their observed cumulative MTBF and cumulative test logarithm time having a linear association. This extension ability of the Crow-AMSAA methodology has allowed for estimations in failure intensity and cumulative failures. In addition to the above models, several repair models have been presented under different assumptions. Block, Borges and Savits (1985) in a study on age – minimal dependent repair, extended the results of preservation and monotonic properties of the result obtained in Brown and Proschan (1983) model. His findings indicated that if an equipment life distribution F has a continuous function, the successive complete repair times exhibits an inter-arrival distribution of Renewal Process model.

The GP model which extends the HPP and Renewal process (RP) models can describe stochastically decreasing trends of the system survival period after repairs. The GP model can also determine the stochastically increasing trends of the repair times after failures. The GP model has been identified to have the ability to model system behaviours within only one of the three failure periods of the bathtub curve per time. Baker & Christer (1994), argued that most models addressing failure intensities lack evident conviction in real-world usability. Furthermore, in buttressing this, pointed out was the absence of indications on how the values of the model parameters derived can be determined as no examples of actual/case study applications or post modelling analysis is often provided (Baker and Christer, 1994). This point raised by Baker & Christer (1994), about most models which address failure intensities lacking evident conviction in real-world usability is addressed in a recent introduction of an Extended Poisson Process (EPP) by Wu & Clements – Croome (Wu and Clements-Croome, 2006). The EPP progression proposed by (Wu and Clements-Croome, 2006) models the three failure periods of bathtub curve system behaviour as shown in Figure 2.7. The periods, namely infant mortality, random failure period and wear out failure period was discussed, and sample sets originated from Davis (1952), is utilised in estimation and demonstrating the validity of the new EPP process (Wu and Clements-Croome, 2006).

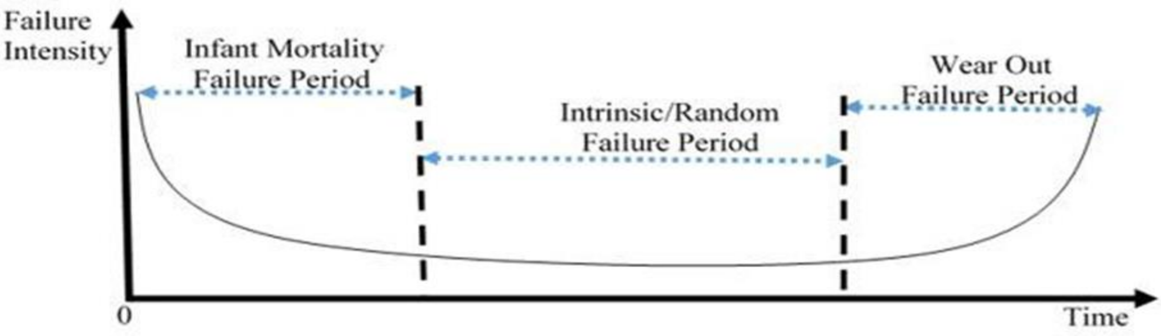

Figure 2-7 Bathtub Curve

In addition to the challenge that most models which address failure intensities lacking evident conviction in real-world usability as noted by Baker and Christer (1994), another issue is the methods for assessing the dependence of failure time to the event on explanatory variables. However, Kalbfleisch and Prentice, (2011) believe the problems of estimations and specification of models for the underlying failure time of events distributions is distinctive (Kalbfleisch and Prentice, 2011). Data types determine the analysis type that can be performed and the most appropriate statistical method. RGA is often supported by developmental or fielded data as shown in Figure 2.8. While development data (i.e. time to failure data, discrete data, multiphase data, reliability data) are obtained from in-house conducted reliability growth testing usually during development stage testing of a system, on the other hand, fielded data (i.e. repairable data and fleet data) are acquired from repairable systems operating if the field under real-time customer usage.

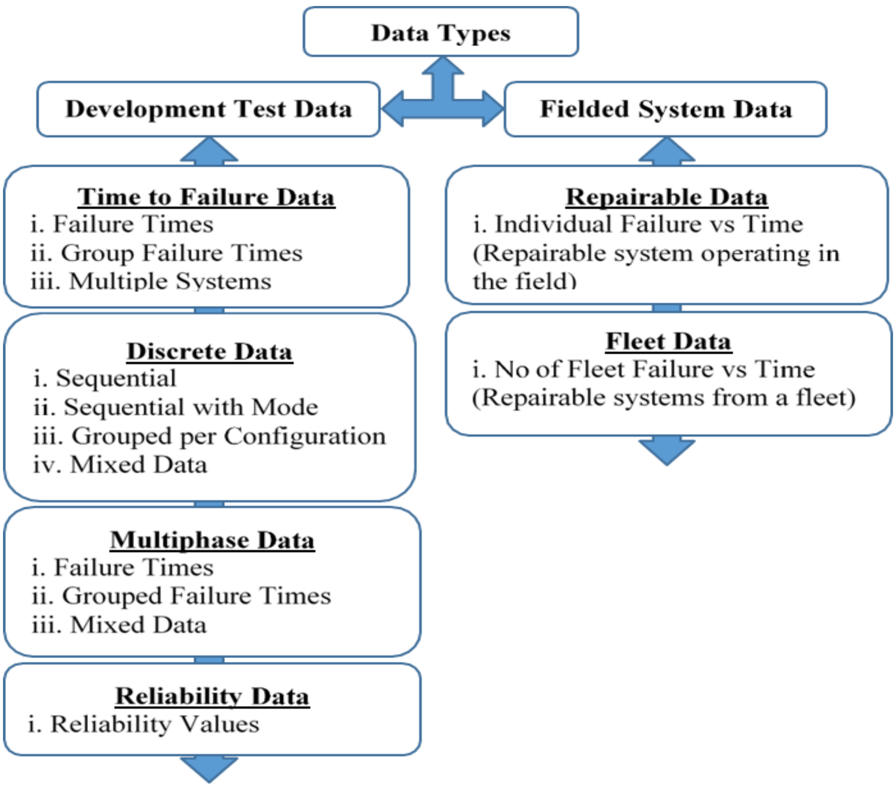

Figure 2-8 Depiction of Data Types Supported by Reliability Growth Analysis

Adapted: (ReliaSoft Corporation, 2015)

2.8 MODELLING PERFORMANCE AND UNCERTAINTY

In planning and implementation of life expectancy model, the understanding of estimations of life expectancy dependence of quantitative method is essential (Thompson et al., 2012). Life expectancy depends on quantitative models to determine asset deterioration regarding condition or performance. On the estimation of life expectancies for assets of the highways industry, the performance which is the ability of an asset or group of assets to satisfy customer or stakeholder expectations is considered most significant (Ford et al., 2012). In the selection for an appropriate model for a given asset type and application, the peculiarity between continuous and discrete performance measures needs to be understood. In estimating life expectancies for highway assets with the intent to forecast the present and future condition, the distinction between continuous and discrete measure and how it relates to deterministic and probabilistic model plays a vital path.

With deterministic models, the performance at any given point in time is assumed to be known with certainty; such a performance measure is deterministic. A performance measure can represent a continuous performance measure and discrete deterministic performance measure, with continues performance measure having a smooth scale and the discrete performance measure changes on a step-wise scale. However, a continuous probabilistic model describes future performance using a mathematical function for the most likely value and another function to describe the uncertainty surrounding this value. Probabilistic models are often quantified using a constant standard deviation or a standard deviation that increases with time. Unlike the others, the discrete probabilistic model describes each condition state or service level as a probability of that level at each point in time. The models are quantified using a constant transition probability from one state to another state in one year and are known as the Markov model (Zhang et al., 2016).

The Markov Chain model is considered to be a stochastic process because they are discrete in time, having an infinite state space (Costello et al., 2005). Some studies recognised Markov

Chain as an approach applied for the simulation of an asset over time. The simulation from one state (current state) to another state (future condition) is the ideal method to predict deterioration and life expectancies (Karunarathna et al., 2013; Zhang and Gao, 2012; Park et al., 2011; Voskoglou, 2010; Paleologos et al., 2015). Markov Chain establishes the future state of the deterioration process based on its present state. Although Markov Chain is considered as one of the most promising methods to determine assets life that is remaining, the populating of the Markov transition probability remains a concern (Mc Dulling, 2006; Zhang and Brani, 2005).

According to Remenyte-Prescott and Andrews (2013), significant savings have been attributed to the use of the Markov model. The Markov model is the core probabilistic technique asset manager's use in modelling infrastructure systems. Its use has been reported for predicting future conditions, deterioration, and maintenance and service life of infrastructure asset. Mc Dulling (2006) utilised the Markovian model towards the development of transition probability for the prediction of service life in hospital buildings. Other sectors that have benefited Markov Chain application are railways and bridges (Wellalage et al., 2014; Li et al., 2014; Morcous et al., 2003; Wellalage et al., 2015). Infrastructure AM (Han et al., 2014; Kobayashi, 2012). Hydraulic steel structures (Riveros and Arredondo, 2014).The stochastic based life cycle planning (Wightman et al., 2011; Voskoglou, 2010; Costello et al., 2005; Zhang and Brani, 2005). In the modelling of pavement conditions (Ortiz-garcía et al., 2006; Wightman et al., 2011; Surendrakumar et al., 2013) and much more.

In the application of the Markov process to predict asset deterioration, maintenance and service life several observations and assumptions are mandatory. To begin with, the deterioration process of the infrastructure must be continuous in time. Nevertheless, to reduce it discretely in time, the condition is usually evaluated at specific periods which usually correspond to periodic and detailed inspections. After that, the condition of infrastructure is distributed into an infinite number of states. However, in reality, the condition of an infrastructure is defined by a finite set of numbers such as 1, 2, 3, 4,..., 10, where 1 represents the structure in its best possible condition, known as the excellent state, and 10 represents an imminent failure of the infrastructure at a very poor state in a ten-point state condition rating. Where condition rating could be in three-point states as utilised in the SCANNER survey rating by Transport Research Laboratory (2011), 5-point scale ratings by Mc Dulling (2006); Han et al., (2014) and 7 point scale rating by Zhang and Brani (2005) or as desired.

Markov models are characterised by its uniqueness of being able to determine the end of life of a system which differs from the usual regression models used for estimating life expectancy (Woempner, 1993). One of the simplest ways of computing life expectancy was to compute the average age of all demolished assets in a data set. Unfortunately, data issues may make this method impractical or inaccurate in many cases. In exchange for accepting a few simplifying assumptions, the Markov model avoids a great many of the data quality and censoring problems that plague the regression model. Markov Chain model is often compliant with conditions rating capabilities when the conditions are required to be defined in two states namely failed and not failed state. A failed state has been the worst of the conditions defined and not failed as the stages that are not in the failed state category. Markov model is considered to be memoryless because they have the probability of continually jumping from one state to another. Because of the memoryless characteristic, a Markov Deterioration Model can be characterised as a prediction model where the Markov transition probability matrix was utilised in populating future condition forecast. It is suggested by Thompson et al., (2012) that an asset that is entirely in state 1, and repeatedly multiplies by the transition probability matrix until the fraction in the failed state finally reaches 50%. Doing this would simulate the years of the asset's life until half of them have failed, thus giving an estimate of the typical Median life (ML) expectancy of the asset.

The highway assets, especially the carriageway system is well-thought-out as treatable assets because of their defects and failures which are repairable. The condition of the current state of these treatable assets is the base unit for forecasting and implementing their desired maintenance. Maintenance which is a key function for sustaining long-term profitability of assets by organisations is defined as a combination of all actions with intent to retain or restore the asset to its original state or a state where it can perform its required function. In maintaining safety and achieving an optimal state, the carriageway surface could be replaced extensively, moderately or light PM works depending on its current state (Taylor, 2010). The use of optimisation methods helps in achieving the optimal resolution by the proposed goals (Khan and Tee, 2016; Tee et al., 2014).

Optimisation brings benefits such as reducing the cost to maintain a steady state condition, thereby increasing the overall value. Multiyear network planning's and programming with the prospect to improve the total system, towards a defined performance level is achievable by strategic maintenance optimisation. Optimisation approach defines the maintenance scheduling techniques categorised as analytical or simulative methods. Analytical support methods use mathematically based equations in expressing the optimisation problems and solution. The simulative maintenance method finds the optimal maintenance strategy by evaluating different scenarios, thereby portraying its possible consequences. Simulative methods have gained much acceptance in literature as high-speed computers having efficient exploratory optimisation techniques with inbuilt optimisation suites are acceptable in use for asset maintenance and management (Turner, 2002; Dekker, 2006; Cancian et al., 2015).

2.9 SUMMARY

AM plays a significant part in the performance and profitability control of physical assets from their inception all through the operation to their disposal. The necessary level of service and safety expected from the performance of physical asset can be easily accommodated by the introduction of AM whose policy can be judged by the impact to contribute to the value of the physical assets. The services due to the ageing asset are not often delivered anymore as they tend to have reached an age of weakening. Thus, the importance of the AM trend which principles can preserve and enhance network with ageing challenges. The current conditions of the assets and future condition are inbuilt of a good AM framework, having the ability to understand the required service need and how the network under provide their expected function. AM takes great account into inspection of a physical asset, as it is believed that it is mostly via inspections that the actual judgement of the health of the asset can be quantified. The three types of inspection are articulated in the AM framework helps support the various types of the maintenance strategy. With safety inspections tackling risk associated problems, the service inspection tries to optimise PM strategies and the condition surveys help the asset manager to understand the current asset conditions and portray future patterns as well as best decision maintenance strategy.

Several conditions monitoring equipment’s and techniques are developed to collect data on the asset condition, collecting this data thou crucial, requires various statistical tools or model that are supported in the AM framework to give a better understanding of the trends in the data. The user benefits are often most time utilised in measuring the risk, reliability growth and performance of assets but can only give subjective views which change with human circumstances and time. Using objective rules, the information learned from the condition states are of significant benefits to the asset manager with regards to planning maintenance or investing in a new project with consideration of available funding. It is no doubt that the Markov Chain and the Regression Model are the mostly applied model for predicting deterioration of physical assets because of the probabilistic ability. It is a great opportunity for asset managers a carry out a strategic plan for maintenance of asset not as an entity but as a networked system. The value of an asset is often calculated by their construction, operation and maintenance rate, the remaining service life portrayed by a Markov analysis can be used in computing the value of the asset.

The research impact spanned from asset management techniques to the best maintenance method for highway assets that can be applied internationally. Challenges associated with the maintenance of highway infrastructure in Nigeria would also benefit immensely as real time dataset from agencies in the UK were introduced in the application since maintenance records of highway asset is scarcely available in Nigeria. New applications with relation to schedule preventive maintenance for highway asset was introduced using a novel reliability centred maintenance technique. This approach will be impactful to the application with its use in Nigeria as it gives holistic support to all highway assets within the road network. Novel applications the addresses carraigeway of the road network is also deeply investigated in areas such as risk analysis, reliability growth, deterioration and treatments.

CHAPTER 3: RELIABILITY CENTRED MAINTENANCE (RCM)

3.1 INTRODUCTION

Reliability Centred Maintenance (RCM) is a technique that determines the maintenance requirement of a system and the intervals at which these are to be carried out in its operating context through a failure mode effects and criticality analysis (Moubray, 1997; Orugbo et al., 2015). The term RCM as expressed by Nowlan and Heap (1978); Altaf Tarar (2014) defines RCM as a programme designed to realise the inherent reliability capabilities of assets. It focuses on the functions and failures of the assets as well as identifies their consequences. It uses a standardised logical resolution procedure to implement preventive measures from these identified consequences. RCM techniques decide the required maintenance of a system while in its operating environment (Moubray, 1997). The IAM (2008b) classifies RCM as a control that supports optimised management of physical assets. RCM combines different approaches to aid the development of a systematic maintenance programme to manage risks on a basis for maintenance decisions (Backlund, 2005). RCM framework focuses on preserving system functions, rather than preserving physical asset since it offers asset availability and reliability.

RCM has proven to be very beneficiary to several industries (Alan et al., 1999; Park et al., 2011; Huo et al., 2005; Cheng et al., 2008; Siqueira, 2004; Backlund, 2005). The RCM has been of great benefit because the RCM process analysis is structured with a specific tactic to determine the optimal type of PM through a thorough analysis of functional failures, failure modes and failure causes (Rausand and Vatn, 2008). Diverse forms, standards and guidelines of RCM do exist and have been utilised in different scenarios in literature and tailored to different applications. The RCM procedure consists of two methods, namely the classic RCM and back- fit RCM depending on the scenario. Although both methods serve different maintenance situations, they have similar attributes at some points since every RCM process ensures that key question is carefully considered, and justified maintenance requirement recommended by the series of issues. This chapter addresses classical RCM, a maintenance methodology which has the capability of designing an appropriate maintenance programme suitable to sustain the newly created asset with no previous maintenance history. The investigated highway assets in this analysis are drainage, carriageway, footway, road kerb, traffic island, street lighting, traffic signal, road sign, guardrail, road markings and bus shelter.

Unlike Nigeria where highway maintenance still operates the traditional method of run to failure or fix it when broken, the UK highway maintenance programmes are based on an asset management approach which involves using robust data to make good, informed decisions about how to manage and maintain the asset (in this case the highway network) as effectively as possible. This RCM method will help support and lead to good maintenance culture in Nigeria. For instance, it captures and saves exiting maintenance challenges and best solution because another major problem facing the Nigeria highway industry is the lack of knowledge passage from the old and experienced engineers to the young, inexperienced engineers. The contents of this chapter are structured to capture the overview and types of RCM, with the focus on the classic RCM application process. A case study involving key sub-assets of a newly constructed road junction infrastructure in Nigeria is considered in the application using the classical RCM process analysis via the CBR technique and the FMECA strategies presented. Asset functional failures result in the unavailability and downtime which affects their useful capability expectation. Every RCM process should ensure that seven fundamental RCM questions are answered reasonably and are answered in the order as follows (Moubray, 1997),

i. What are the functions of the asset in its present in-service context (functions)?

ii. In what ways can it fail to accomplish its functions (functional failures)?

iii. What causes each functional failure (failure modes)?

iv. What happens when each failure occurs (failure effects)?

v. In what way does each failure matter (failure consequences)?

vi. What should be done to predict functional failure (proactive tasks and task intervals)?

vii. What should be done if a suitable proactive task cannot be found (default actions)?

3.2 TYPES OF RCM: CLASSIC AND BACK-FIT

The classic RCM method is a Preventive Maintenance (PM) system development approach that critically develops and thoroughly analysis preventive and continuous maintenance strategy in an environment of uncertainty with limited operating data for new assets for which no operating history exists. The process of the classic RCM enhances PM of a system, ensuring an accurate mix of PM while providing improved equipment readiness and minimising maintenance cost for possessors of capital assets (CACI International Inc, 2007a). On the other hand, the back-fit RCM is considered as a PM engineering that is applied where sufficient previous operating data exists. The back-fit RCM method is established on operational information on system-dominant failure modes. The improvement and refinement of maintenance during the in-service stages of the life cycle it is core purpose (CACI International Inc, 2007a). It deals with the uncertainty of changing existing maintenance requirements to make the maintenance programme even more useful (U.S Navy Sea Systems, 2007). The classical RCM approach is adopted in this study because its seven steps approached proposed by Moubray (1997) helps capture salient features of highways asset failures.

3.3 CLASSIC RCM PROCESS ANALYSIS

The classic RCM schedules PM by the use of available resources when little to no operational experience exists for a system, asset or equipment securing the right fusion of preventive and corrective maintenance tasks (CACI International Inc, 2007b). The c-RCM develops maintenance task for new systems by first partitioning the system into assets and sub-assets that require analysis, and after that, the functionally significant items are identified. The needed maintenance tasks for each important item is based on analysis of its functions, its dominant failure modes and the risk associated with its functional failures are then determined. A literature review of c-RCM methods reveals that only the classic RCM methodology can take a top-down, zero-based approach to maintenance analysis (Moubray, 1997). This classic RCM process, as outlined in Table 3.1, consists of twelve phases divided into three segments with key emphasis on system partitioning, FMEA with decision logic and maintenance strategy with task adoption (U.S Navy Sea Systems, 2007).

Table 3-1 Classic RCM Approach

Phase	Description	Purpose
Segment 1 Detailed knowledge about the system and its functions are gathered to enable good decisions about failures will be the most concern in the intended system application.		
Phase	**Description**	**Purpose**
1	Partitioning: Functional block diagram and index	Determine system boundaries, interfaces and functions
2	Functional failure analysis	Describe system/subsystem, functions and interfaces. Identify active and passive failures
3	Other functionally significant item selection and functionality significant item index	Identify functions and functional failures at levels of indenture below subsystem
Segment 2 All failure modes that could result in the system to loss of system function is considered, and the failure modes with the greatest risk are determined. The best course of action to address these dominant failures is then determined by a decision logic tree analysis.		
Phase	**Description**	**Purpose**
4	FMEA	Determine dominant failures identify the effect (consequences) of failure
5	RCM decision logic tree analysis	Identify the need for a maintenance task, determine if the proposed task is applicable and effective
6	Servicing and lubrication analysis	Use instead of step 5 to evaluate routine servicing and lubrication requirements
7	Audit and preparation of the maintenance requirement:	List all proposed maintenance tasks for review and approval
Segment 3 Maintenance task developed from the application of the decision logic tree is combined into the detailed procedure for accomplishment with consideration to materials, workforce and training required to obtain the best and appropriate maintenance procedure.		
Phase	**Description**	**Purpose**
8	Method study and evaluation of new task	Develop the most practical method of accomplishing each task
9	Maintenance requirement task	Determine appropriate maintenance level
10	Inactive equipment maintenance	Develop a procedure to a layup, preserve, reactivate and test inactive equipment
11	Unscheduled maintenance	Develop a way for returning systems/equipment to service following corrective maintenance
12	Maintenance required cards preparation	Prepare Maintenance Index Page and MRC

Adapted: (Smith and Hinchcliffe, 2004; U.S Navy Sea Systems, 2007)

3.3.1 System Partitioning

The system partitioning help identifies all the technical information of functionally significant items. Partitioning along significant asset and sub-asset boundaries help facilitate the RCM analysis and specify the boundaries scope and approach (MIL-STD-2173, 1986). The asset descriptive and operational information are gathered from traditional expert judgement and highway asset maintenance literature. The asset status (i.e., asset defect, defect categories, defect period, repair hours, repair cost) as related to the individual asset are retrieved from an NMMS database Code of Practices such as UK Lighting Board (2004); UK Bridges Board (2005); UK Roads Board (2005) and relative literature (Orugbo et al., 2012).

3.3.2 Failure Mode and Effect Analysis (FMEA)

The principal causes of functional failure are identified in this qualitative method process which aims to find the failure mode of the asset and analyse the failure mode in an operational or fielded system. This step is the most important phase in the RCM analysis as it gives the necessary information for decision logic analysis as well as the quality of the proposed PM programme. It captures assets functions, functional failure, failure modes and failure effects. The functional failure is an unsatisfactory condition which results from an asset not providing its intended function. The specific situation causing the functional failure is known as a failure mode, while the arising consequences are called failure effects (Huo et al., 2005).

3.3.3 Decision Logic and Criticality Analysis

The decision logic and criticality analysis adopted and expressed in RCM uses decision rationality of Yes and No questions to find an optimal balance between the best maintenance tasks since making a decisive judgement from old-style expert judgements in highway asset maintenance is difficult. Maintenance tasks in this approach are chosen based on eight decision logic questions as shown in Table 3.2 with consideration of the criticality classes. Questions 1-3 determines the failure classification while other questions are used for consideration of the most appropriate and practical task. As shown in the criticality analysis classification in Table 3.3, the effectiveness in Question 4-7 is utilised in producing the criticality class and rules used to verify if the proposed tasks are useful (U.S Navy Sea Systems, 2007).

Table 3-2 Decision Logic Questions

DECISION LOGIC TABLE			
Question	**Logic**		**Decision**
1	Is the occurrence of failure evident to the operating crew while it is performing its normal duties?		Yes = Go to Question 2 *Evident Failure*
			No = Go to Question 7 *Hidden Failure*
2	Does the failure cause a loss of function or secondary damage that has a direct and adverse effect on operating safety?		Yes = Go to Question 4 *Safety Capability*
			No = Go to Question 3 *Operational Capability*
3	Does the failure have a direct and adverse effect on operational capability?		Yes = Go to Question 5 *Operational Capability*
			No = Go to Question 6 *All Others*
4-7	Is there an effective and applicable PM task that will prevent functional failures?		
	Effectiveness		Rules
	Q4	Safety & Environment	The probability of failure reduced to very low
	Q5	Mission	Risk of failure reduced to an acceptable level
	Q6	All Others	Cost of maintenance less than the repair cost
	Q7	Hidden Failure	Consequences of hidden failure *Yes=Describe/Classify; No= Go to Q8*
8	Is a scheduled failure finding task available and justified?		Yes = Specify the task
			No = Consider the safe design

Table 3-3 Criticality Analysis and Class Arrangement

CRITICALITY ANALYSIS			CRITICALITY CLASS
1	2	3	
Y	Y	N/A	A=Safety/Environments
Y	N	Y	B = Mission
Y	N	N	C = Hidden Failure
N	N/A	N/A	D = All Other Function

3.3.4 Maintenance Task Improvement:

The maintenance task improvement comprises developing PM tasks and combining effective PM policy. The recommendation from the classical RCM study and the comparison to the existing PM task programme is expressional which is very important. Existing maintenance classifications and intervals are very useful in developing the PM programme for new assets (Cheng et al., 2008). Evaluation of the various maintenance task in Table 3.1 and the testing of the limits of the recommended maintenance tasks would improve the maintenance system.

3.4 CASE-BASED REASONING (CBR)

The CBR is a technique that utilises solutions gained from experience or knowledge encountered in a similar situation. CBR is a problem solving and learning approach which is used to solve the current problem considering prior experience gained from similar problems solved in the past (De-Mantaras et al., 2005). The CBR approach strengthens the weakness of the classical RCM with limited operating data. The similar anticipated functional failure of the identified highway assets are retrieved from the UK based Code of Practices and NMMS for highway infrastructures. After that, it is reused in relation to the boundary of predicted functional failure of highway asset analysed for this study and revised after designing the failure mode and effects of the associated assets. Decision logic is applied to the FMEA to assign a correct maintenance strategy and periodicity for maintenance tasks.

This analysis comprises the application of the various segments of the CBR into the classic RCM approach. In the CBR terminology, a previous situation, which has been captured and learned is stored in a way that it can be reused in the solving of future problems (Aamodt and Plaza, 1994). A CBR cycle uses a 4R cycle system namely (i) Retrieve, (ii) Reuse, (iii) Revise and (iv) Retain are coined in between the 6 stages of the CBR cycle namely (i.)New case, (ii) Case library, (iii)Similar case, (iv) Derived solution, (v) Learned case and (vi) Knowledgebase as shown in Figure 3.1. A new case or unsolved case is the description of a new problem to be solved. Mantaras expressed the importance of the use of CBR in solving current challenges. He stated that the current problem is best understood by measuring its comparison with similar previous problems stored in a case-based memory and other suitable database and having their known solution (De-Mantaras et al., 2005). In CBR, an earlier situation that was previously captured and learned is reused in the solving of future problems.

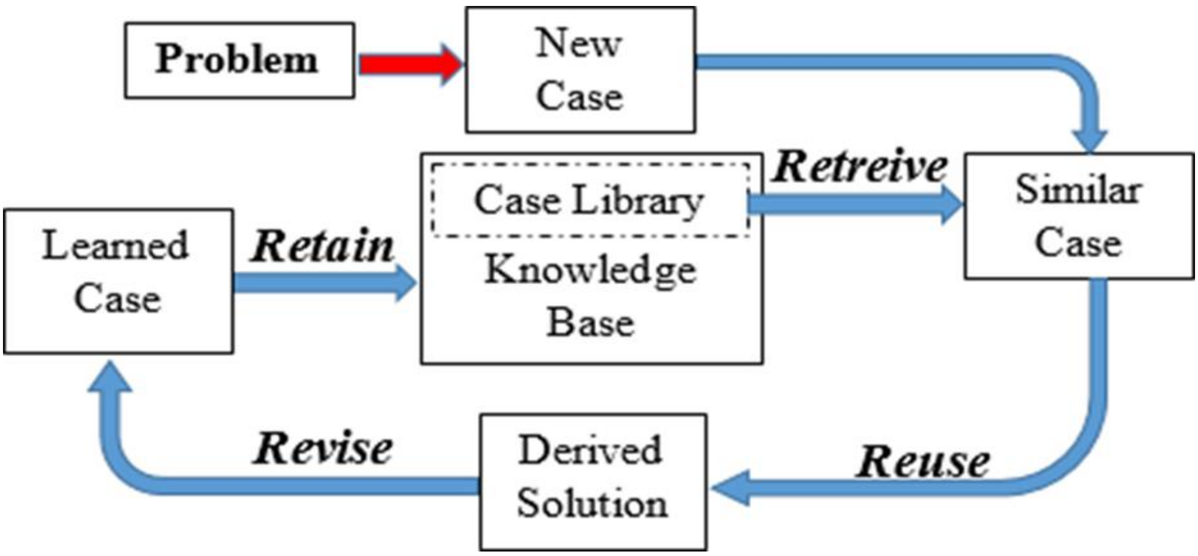

Figure 3-1 4R's Case-Based Reasoning (CBR)

Adapted: (Aamodt and Plaza, 1994)

3.5 ROAD JUNCTION SYSTEM AND ASSET ANALYSIS

Ageing of systems and the need for digital asset database are some of the key importance of the AM discipline. The context of AM is imperative for optimisation of the highway infrastructure as it implements key decisions for the design, operation, maintenance, inspection, renewal enhancement and disposal of these physical assets to deliver safe and economic infrastructure. AM is essential for continuous availability of the road junction assets as its discipline integrates maintenance and replacement analysis with economics and system failure analysis (Remenyte- Prescott and Andrews, 2013). A road junction system in the Niger Delta Region of Nigeria, called Enerhen road junction, is considered in the case study. The road junction is newly constructed, thereby having no previous maintenance records. Unlike the UK and other developed countries where the actual operating history and techniques for dealing with maintenance uncertainties are understood, Nigeria road transport industries, though carry out maintenance still maintain highway assets on the run to failure and corrective maintenance style.

Introducing CBR into the RCM process analysis strengthens the weakness of the classic RCM in which the approach is used for new situations where limited, or no operating data exists. This approach improves the efficiency of RCM analysis by reducing or avoiding repeated analysis of assets by an expert (Garozzo and Andrea, 2006). The solutions are tested on real-time newly created road junction infrastructure system as illustrated in later sessions of the chapter. Ensuring continuous availability and reliability of these newly constructed road junction assets which comprises of complex physical assets requires defining their function, units and quantity. A classical RCM method utilising a CBR approach is conducted for the newly installed vital road transport assets at road junction by the research group consisting of the design /project engineer involved in the whole construction and installation of the assets and experts in highway infrastructure maintenance in the United Kingdom. The use of CBR in modelling the RCM the highway assets entails the following four steps.

First, the newly created highway assets in Nigeria was selected as a new case while all other highways assets information in the UK codes of practice and UK NMMS dataset stands for case library in the Knowledgebase. The goal is to predict the condition of the asset if no maintenance is carried out. Secondly, the process called retrieval is implemented by the search in the UK codes of practice and UK NMMS dataset to find the most similar stored cases in the case library. The knowledge base has a similarity of failure types, causes and the effects on road users. These information's are retrieved from related surveys, literature and experts' database and are reused in modelling the faults, failure modes and maintenance task. The cases are retrieved with the intent to reuse the solution arrived in the earlier cases to address that of the new case. The attribute of a new case that represents the highway asset information is then captured with the focus of the asset information. The definitions of the asset functions, the various ways the assets do not perform their function, the modes of failure of the assets and the effects of these failures and the consequences of these failures. This section is used to propose the FMEA analysis.

Thirdly, the asset information projected from the FMEA is utilised to conduct a criticality analysis of the asset based on the four keys criteria's namely safety and environmental criticality, mission criticality, other criticalities, and hidden failure criticalities. Maintenance data saved in an NMMS is retrieved and reused in solving the expected functional failures which are likely to arise in the RCM analysis. It is stated that the current problems are best understood by measuring its comparison with similar previous problems stored in a case-based NMMS (Berneski, 2014). The process wish is called reuse help shows the assets critical failure modes and how it affects road users. Finally, the last process is known as the case retaining stage. The new information about the various assets (e.g., inspection and maintenance data) are now used to support the newly created asset as a guide when failures occur and best inspection regime with maintenance task available to support them. The solution arrived is then evaluated by either direct application or domain expert, and if favourable, it is retained as a new case, and the system learns how to solve such new problems.

3.5.1 Step 1 – Problem Related with New Case

Delta State Government, Nigeria embarked on an ambitious strategy in the year 2013 to significantly improve the reliability of its road junction systems. Its existing road junction systems constructed over 50 years ago, as shown in Figure 1.1, had exceeded its useful life and it lacked availability of crucial road junction assets. During severe conditions such as rain and flooding, it was consistently shut down for extended hours principally due to the unavailability and inoperable road junction assets. The unavailability of the highway asset as stated by the consultant's leads to high traffic congestion and high-risk to all road users (i.e., motorist, cyclist and pedestrians) and absolute menace at the road junction. The additional issue at the junction included the following (i.e., No traffic signals / of non-functional; no lane marking; deteriorated road pavement; poor drainage system with silted drains; vehicle-passenger conflicts; no provision for walkways for pedestrians). This led to increased congestion and the attendant loss of productive person-hours, road traffic accidents, high environmental and noise pollution, and the growth of the market and other economic activities around the road junction (A.I.L Infrastructure Limited, 2013).

In a comparative study of defects liability period in Nigeria, it is noticed that the occurrence of defects after the defects liability period in Nigeria is higher than other countries because of a shorter defects liability period of 6 months. As a result, it does not give a reasonable time for defects to manifest (Oluwole et al., 2012). Defects liability period of 6 months is equivalent to the warranty period owned by the owners. Within this period the contractors repair any defects associated with the assets. Little to no maintenance data is usually recorded within this period as highway assets usually have a longer time to failure than their defects liability periods. The short defect liability period provides asset owners with no maintenance records but to rely on experience, expert judgements, corrective maintenance or run to failure strategies to ensure continuous availability and reliability of their assets when a failure occurs. For this reason, the junction improvement work of the failed road junction network in Niger Delta, Nigeria presented in Figure 1.1 started early 2013 and completed September 2013 with all crucial new road junction assets installed as shown in Figure 3.2. The junction depicting its view in Figure 3.2 is proposed as the new case for the analysis.

Figure 3-2 Newly Constructed Road Junction Network in Niger Delta, Nigeria

Source: (A.I.L Infrastructure Limited, 2013; Ekpiwhre and Tee, 2015, 2016b)

3.5.2 Step 2- Retrieve of Similar Problem from Knowledge Base

The second segment of the classical RCM analysis is the system selection of the assets whose critical failure modes would diminish the operations of the junction system. The selected assets for this investigation are drainage system, carriageway, footway and cycleway, road kerb, road restraint system, traffic signs and bollards, road markings, traffic signals and pedestrian crossing as well as road lighting. The asset functions are first defined before making decisions about what dominant failure modes are the most crucial to the system application. The assets are partitioned as shown in Table 3.4 to display the disparity between various functions of the assets of the road junction system. They are further broken down into sub-assets to enable the assembly team to determine system boundaries, interfaces, functions, and functional failure.

Table 3-4 Partitioned Assets of Investigated Road Junction System in Nigeria

No	DESCRIPTION	UNIT	QTY	FUNCTION
1.	DRAINAGE			*To allow for the removal of water from the carriageway and surrounding catchment areas*
1.10	Linear drainage	L.in.m	760	
1.20	Concrete Drain Cover	L.in.m	760	
1.30	Culvert	L.in.m		
2.	CARRIAGEWAY			*To facilitate reliable journey time for vehicular road and cyclist*
2.10	Compacted crush stone	Cu.m	200	
2.20	Bituminous	Sq.m	1,080	
2.30	Asphaltic wearing course	Sq.m	8,900	
3	FOOTWAY			*To create a safe way for pedestrians to move about on a path that is separated from the carriageway.*
3.10	Precast concrete kerbs	L.in.m	870	
3.20	Precast footway paving stones	Sq.m	5,904	
4.	TRAFFIC MEDIAN/ISLAND			*To help calm traffic and improve ease of pedestrian crossing or (in limited circumstances) carries traffic control equipment*
4.10	Road Median/Traffic Island	L.in.m	280	
5.	ROAD LIGHTING			*To provide visibility at night hours by illuminating the surface and adjacent features of the roadway and sidewalk*
5.10	Street Lighting	No	40	
6.	ROAD SIGNS			*To guide and regulate traffic, communicating information clearly and with sufficient time*
6.10	Road signs	No	100	
7	TRAFFIC SIGNALS			*To assign right of way to lanes to individual streams in turns*
7.10	Control Cabinet	No	1	
7.20	Poles and components	No	4	
7.30	Cameras	No	4	
8.	ROAD RESTRAIN			*To segregate pedestrians from vehicles and helps channel pedestrians to where they are supposed to be walking,*
8.10	Guardrail	m	740	
9.	LANE MARKINGS			*To provide information and warning to road users and help guide traffic flow in an orderly, safe stream*
9.10	Road Marking	m	1,680	
10.	BUS TERMINAL			*Helps provide shelter for passengers waiting to board or alight from the bus*
10.10	Bus Shelter	No	3	
			21,326	

3.5.3 Step 3: Adaptation and Reuse of Suggested Solution for New Case

After systematically bounding and describing the road junction system assets, the next classical RCM step is to document the functions and performance parameters of the assets. For instance, the primary function of the drainage system is to provide a means of collecting and removal of water from rainfall or other sources such as from carriageway and surrounding catchment areas as portrayed in Table 3.5, after that transferring the wastewater to a designated discharge point. From this system function, three functional failures are listed as follows:

i. The drainage system does not take away rainwater.

ii. The drainage system does not hold and transfer wastewater.

iii. The drainage system does not protect from environmental pollution.

All failure modes that could result in the loss of system functions are considered, and the failure modes with the most significant consequences are determined by carrying out an FMEA. Although functional failures and failure modes on highway assets are numerous as addressed in the UK Lighting Board, (2004); UK Roads Board, (2005); UK Bridges Board, (2005); Orugbo et al., (2012), the analysis projected twenty-six relevant critical functional failures and failure modes for all the ten asset /seventeen sub-assets for this analysis as depicted in Table 3.5.

Table 3-5 FMEA of Highway Assets in the United Kingdom Collected Works

ASSET	S/N	FUNCTION	FUNCTIONAL FAILURE *Non-fulfilment of function*		FAILURE MODE *Cause of failure*		FAILURE EFFECT *Consequences*
Drainage	01	To allow for the removal of water on the carriageway and surrounding catchment areas	A B C	Fails to take away rainwater Fails to discharge or contain rainfall Fails to protect from environment pollution	1 1 1	Blocked Drains (edge drains affected by sedimentation and debris accumulation) Design (wrong discharge design, damaged or inappropriate rainfall containment) Dilapidated and ineffective pollution control devices	Public safety, destruction of existing road infrastructure, inefficient travel, increase travel time, disrupt intended flow and operating speed, discomfort and inconveniences to the road users and reduced appearance of road aesthetics and appeal
Carriageway	02	To facilitate a smooth and reliable journey time	A B	Fails to facilitate smooth Drive Fails to provide a reliable journey	1	Deterioration Texture and reduced resistance to skid Defected carriageway by longitudinal and transverse crack, pothole, poor texture, poor skid resistance and lousy edge condition)	Affects vehicular and cyclist safety, comfort and convenience, Increased vehicle maintenance cost impact of the economy., inefficient travel time, and poor appearance of local aesthetics and appeal
Footway	03	To create a safe way for pedestrians to move about on a path that is separated from the carriageway	A B C	Fails to provide a safe walk path Fails to ease the convenient path Fails to provide friendly walk path	1 1 1	Pavement distress, spalling, cracking, surface irregularity Weather, poor design, faded markings Debris accumulation	Affects pedestrian and cyclist safety, comfort and convenience, poor accessibility to transits or bus shelters, inefficient travel, increased time
Traffic Island	04	To help calm traffic and improve ease of pedestrian crossing or (in limited circumstances) carries traffic control equipment	A B C	Fails to calm, separate opposite flow of traffic Fails to ease pedestrian crossing Fails to accommodate equipment safety	1 1 1	Vehicles capable of crossing over Inaccessible pedestrian route, debris accumulation, inappropriate tactile surface Accident damage, age- use related factors	Affects pedestrian and cyclist safety, comfort and convenience, poor accessibility to transits or bus shelters, inefficient carriageway crossing, and poor appearance of local aesthetics and appeal
Road Lighting	05	To provide visibility at night hours	A B C	Fails to stand and hold lamp unit properly Fails to appropriate signals to the lamp Fails to light up or light up designated area adequately	1 1 1	Damage to post or arm (accidents, improper installation, age-related) Flaws from photocells, ballast or other components Non-functional components (lamps, ballast photocells)	Public safety majorly at night, road users comfort and convenience compromised, less efficient travel and operating speed, crime increase at night and poor appearance of road aesthetics and appeal

ASSET	S/N	FUNCTION	FUNCTIONAL FAILURE *Non-fulfilment of function*		FAILURE MODE *Cause of failure*		FAILURE EFFECT *Consequences*
Road Sign	06	To guide and regulate traffic, communicating information clearly and with sufficient lead-time	A B C	Fails to hold sign display uprightly or display carriageway written signs clearly Sign panel fails to send appropriate feedback to road users Signs panels illegible	1 1 1	Sign panel support damaged, vandalism, inappropriate maintenance Deteriorated sign panel (poor reflectivity, faded colouring, weathering) Faded	Increase rates of a near miss with safety implications, frustration to road users, less efficient travel and due to deteriorated signs, operating speed & discomfort and inconveniences to the road users and poor appearance
Traffic Signal	07	To guide and regulate traffic, communicating information clearly and with sufficient time	A B C	Fails to hold signal display unit uprightly Fails to send an appropriate signal to display unit Fails to assign correct advice to road user	1 1 1	Mast and arm damage due to damage, accident or age and use Defects on controller and detectors cause by corrosion, wreathing. Non-function component (signal display unit, controller, detectors)	Public safety, accident and accident risk increase, inefficient travel, increase travel time, disrupt the intended flow and operating speed, discomfort and inconveniences to the road users and poor appearance of road aesthetics and appeal
Road Barrier	08	To segregate pedestrians from vehicles, help channel pedestrians to where they are supposed to be walking, mainly those with visual impairment	A B	Fails to segregate Fails to direct	1 1	Inadequate offsets, poor post spacing, embattlement and splicing, damaged or age-related factors. Deteriorated Road Safety Barrier, dull declination devices, missing parts	The motorist, cyclist and pedestrian's safety compromised as head impact criterion is increased, reduced appearance of local aesthetics and appeal
Road Marking	09	To provide information and warning to road users and help guide traffic flow in an orderly, safe stream	A B C	Fails to guide traffic Fails to reflect feedback on road users Fails to provide information	1 1 1	Paint for a lane, and edge striping abraded, wear and loss of adhesion (Ultra Violet rays, heat traffic and road surface grime) Loss of reflectivity (reduced by dirt, abrasion and weathering) Raised pavement marker unavailable (degradation, dirt accrual, heat wear)	Road user's safety compromised due to illegibility which decreases the road user's decisions, discomfort and inconveniences to road users, sparse appearance of local aesthetics and appeal
Bus Shelter	10	To provide a safe place where passengers wait to board and alight from a bus	A B	Fails to shelter passenger safely Fails to inform passenger adequately	1 1	Damaged (vandalism, age–user related, weathering) Information unavailable (lack of inspection)	Passengers affected by harsh weathering condition, accidents or accident risk from trips and fall prior boarding or alighting from the bus

Adapted: (UK Lighting Board, 2004; UK Roads Board, 2005; UK Bridges Board, 2005; Orugbo et al., 2012)

3.5.4 Step 4 – Confirmed Solution for Retainment as Learned Case

The results from the application of decision logic tree analysis devised from the classic RCM process analysis in Segment 2 Phase 5 of Table 3.1 is used to develop an appropriate maintenance programme for the associated road junction transport assets to ensure continuous functionality and availability. The most appropriate method for accomplishing each maintenance task is recommended. It is observed that the best way to determine the ideal intervals should be based on information about the failure rate function, the consequences and cost of the failure. The PM task is supposed to prevent as well as reduce cost and mitigate the risk of the PM tasks (Rausand and Vatn, 2008). The dominant failures as they affect user safety, mission and environment are determined by a critical decision logic framework as shown in Table 3.6 to Table 3.15 for the investigated asset. The analysis utilises the fundamental eight decision logic questions as indicated in Table 3.3 to determine the criticality class by conducting a criticality analysis for the asset with emphasis on the following.

A. Safety and Environment Criticality

B. Mission Criticality

C. Other Criticalities

D. Hidden failures Criticality

For illustration, the effectiveness priority assessment for drainage system as illustrated in Table of 3.6, demonstrates that the criticality classes associated with three functional failures as detected by logic analysis are B, B & A where A is for safety and environment criticality and B for mission criticality. A full breakdown of 1A of Table 3.6 is expressed below, presenting how the analysis for the various failure function of the assets is steered.

I. Criticality Analysis (CA):

Question 1. Is the occurrence of a blocked drainage failure evident to the operating crew while it is performing its regular duties? Yes – Because the debris reveals itself to the drainage inspection crew on their day to day activities

Question 2. Does the Blocked drainage failure cause a loss of function or secondary damage that has a direct and adverse effect on operating safety? Yes

Question 3. Does the failure have a direct and adverse effect on operational capability? No

The CA results portray the answers as follows Q1=Yes (Y), Q2. =Yes (Y) and Q3. = No (N)

Y, Y, N is the CA equivalent of a 4 (safety and environmental criticality) in the criticality class table for a PM task consideration as indicated in Table 3.3.

II. Preventive Maintenance Task (PM Task):

Question 4. = Is the effectiveness of safety and environment criticality related? Yes (Y)

Question 5. = Is the effectiveness of mission criticality related? No (N)

Question 6. = Is the effectiveness of other criticalities related? No (N)

Question 7. = Is the effectiveness of hidden failures criticality related? No (N)

The resultant from a PM task of No 4 (safety and environmental criticality) requires that the probability of failure to be reduced to very low.

Question 8. Is a scheduled failure finding task available and justified? Not applicable

III. Finding Task (FT): Yes

IV. Redesign (RD): No

V. Preventive maintenance Strategy (PS): CD task requires a periodic diagnostic inspection that compares the existing condition of the drainage system with the design standard. This help discovers and correct potential failures before an actual failure occurs.

VI. Description (D): Maintenance activity to be recommended

VII. Periodicity (P): Mean Time between Inspections (MTBI)

Table 3-6 Drainage System

FF/ FM		CA			CS	PM TASK				FT	RD	PS	D	P
		1	2	3		4	5	6	7					
1A 1B 1C	**Functional Failure** Fails to take away rainwater Fails to contain rainfall runoff Fails to protect from environment pollution													
1A1	**FM** Blocked drainage (edge drains affected by Sedimentation) /debris accumulation	Y	N	Y	B	Y	N	N	N	YES	NO	CD	Cleaning More frequent Safety Inspection/ Redesign Espouse time-based maintenance	MTBI is every two years
1B1	Poor design (wrong discharge design levels, damaged or inappropriate rainfall containment)	Y	N	Y	B	N	Y	N	N	YES	NO	CD		
1C1	Dilapidated and ineffective pollution control devices (full /bypass interceptors, silt removal)	Y	Y	N	A	Y	N	N	N	YES	NO	CD		

Table 3-7 Footway

FF/ FM		CA			CS	PM TASK				FT	RD	PS	D	P
		1	2	3		4	5	6	7					
2A 2B 2C	**Functional Failure** Fails to provide a safe walk path Fails to provide convenient walk path Fails to provide unfriendly walk path													
2A1	**Failure Mode** Pavement distress (spalling, cracking, surface irregularities, rutting, rocking, depression, unzipping, potholes, bumps and damaged)	Y	N	Y	B	N	Y	N	N	YES	NO	CD	Safety inspection that is hazardous (trips, potholes, flags, missing pavers, ruts &depressions)	MTBI is every three months
2B1	Surface type and size (unfriendly with the weather condition, poor design, faded painted markings)	Y	N	N	C	N	Y	N	N	YES	NO	CD	Detailed inspection (includes all safety inspection, irregularities, structural balance)	MTBI is at yearly intervals
2C1	Debris accumulation	Y	Y	N	-	N	Y	N	N	YES	NO	TD		

Table 3-8 Traffic Island

FF/ FM		CA			CS	PM TASK				FT	RD	PS	D	P
		1	2	3		4	5	6	7					
	Functional Failure												Inspection to ensure that all island surface is non-slippery by ensuring it tactile are still intact, and no accumulation of debris or displacement of asset laid off	MTBI is every two years
3A	Fails to calm, separate opposite flow of traffic.													
3B	Fails to ease pedestrian crossing													
	Failure Mode													
3A1	Vehicles capable of crossing over	Y	N	Y	B	N	Y			YES	NO	CD		
3B1	Inaccessible pedestrian route, debris accumulation Inappropriate tactile surface	Y	N	Y	B	N	Y			YES	NO	CD		

Table 3-9 Road Light

FF/ FM		CA			CS	PM TASK				FT	RD	PS	D	P
		1	2	3		4	5	6	7					
	Functional Failure												Safety inspection (performance of lighting) DVI & maintenance (Luminaries, columns, network cabling, feeder pillar, switch room and distribution power points) Electrical test & inspection	MTBI safety inspection is between 14-28 days interval During bulk lamp change which is 12 months /4000 hours interval for bulk lamp change
4A	Fails to stand and hold lamp unit uprightly													
4B	Fails to appropriate signal to the lamp													
4C	Fails to light up lamp adequately													
4D	Fails to display clearly													
	FM													
4A1	Damaged (post and arms)	Y	Y	-	A	Y	N	N	N	YES	NO	CD		
4B1	Corrosion (flaw on photocells and ballasts)	Y	Y	-	A	Y	N	N	N	YES	NO	CD		
4C1	Non-Functional component (lamps, ballast, photocells)	Y	Y	-	A	Y	N	N	N	YES	NO	CD		
4D1	Use –time-related factor (Blurred casing, dirt accumulation)	Y	N	Y	B	N	Y	N	N	YES	NO	CD		

Table 3-10 Road Signs & Bollards

FF/ FM		CA			CS	PM TASK				FT	RD	PS	D	P
		1	2	3		4	5	6	7					
5A 5B 5C	**Functional Failure** Fails to hold sign display uprightly Fails to send appropriate feedback to road users Fails legible												Safety inspection (Night time patrol) Detailed inspection (Visual performance, cleaning, obscured sign, signpost structural & mechanical integrity) Bulk lamp change	MTBI between safety inspection is 14 -28days 12-24 monthly interval 6/12/24 months interval based on lamp type or by producer's instructions
	Failure Mode													
5A1	Sign Panel or support damaged, vandalism, inappropriate maintenance	Y	N	Y	B	N	Y	N	N	YES	NO	CD		
5B1	Deteriorated sign panel (poor retro-reflectivity, faded colour, weathering)	Y	Y	-	A	Y	N	N	N	YES	NO	CD		
5C1	Obscured sign (vegetation, blistering, dirt accumulation and missing signs, insufficient inspection)	Y	N	N	B	N	Y	N	N	YES	NO	CD		

Table 3-11 Traffic Signal

FF/ FM		CA			CS	PM TASK				FT	RD	PS	D	P
		1	2	3		4	5	6	7					
6A 6B 6C	**Functional Failure** Fails to hold signal display unit uprightly Fails to send an appropriate signal to display unit Fails to assign correct advice to road user adequately												Safety check-up of & replacement of electro-mechanical parts, backup batteries. Lamp changing and lens cleaning	Yearly interval and replaced based on producer's directions Checked six months interval but changed yearly
	Failure Mode													
6A1	Damage (mast arm and poles)	Y	Y	N	A	Y	N	N	Y	YES	NO	CD		
6B1	Corrosion (defect on controller & detector)	Y	Y	N	A	N	N	N	Y	YES	NO	CD		
6C1	Non-functional component signal display)	Y	N	-	D	N	N	N	N	NO	YES	CD		

Table 3-12 Carriageway

FF/ FM		CA			CS	PM TASK				FT	RD	PS	D	P
		1	2	3		4	5	6	7					
7A 7B	**Functional Failure** Fails to facilitate a smooth ride Fails to facilitate the reliable journey													
	Failure Mode													
7A1	Deterioration Texture and skid resistance	Y	Y	N	A	N	Y	N	N	YES	NO	CD	Detailed Inspection /Survey Safety Inspection/redesign	MTBI is at intervals monthly
7B1	Defected carriageway by longitudinal and transverse crack, pothole, poor texture, poor skid resistance and bad edge condition	Y	N	Y	B	N	Y	N	N	YES	NO	CD		

Table 3-13 Road Restrain Barrier

FF/ FM		CA			CS	PM TASK				FT	RD	PS	D	P
		1	2	3		4	5	6	7					
8A 8B	**Functional Failure** Fails to segregate Fails to direct													
	Failure Mode													
8A1	Inadequate offset, poor post spacing, embattlement and splicing, accidents, age-related factors)	Y	N	Y	B	N	Y			YES	NO	CD	Cleaning More frequent Safety Inspection/ redesign Espouse time-based upkeep	A yearly MTBI is attributed to enabling checks on structure and paintings
8B1	Dull delineation devices, missing parts	Y	N	Y	B	N	Y			YES	NO	CD		

Table 3-14 Road Markings

FF/ FM		CA			CS	PM TASK					RD	PS	D	P
		1	2	3		4	5	6	7					
9A 9B 9C	**Functional Failure** Fails to guide traffic Fails to reflect feedback on road users Fails to provide Information													
	Failure Mode													
9A1	Paint for a lane, and edge striping abrade, wear and loss of adhesion (degraded by UV rays, heat, traffic and road surface grime)	Y	N	Y	B	N	Y			YES	NO	CD	High-speed monitor and visual inspection to assess retro-reflectivity, wear assessment, assessment of luminance factor and measurement of skid resistance	MTBI is on an annual interval CAT 1 defects corrected with 24hours, while CAT 2 defects within six months)
9B1	Loss of reflectivity (reduced by dirt, abrasion and weathering)	Y	N	Y	B	N	Y			YES	NO	CD		
9C1	Raised pavement marker broken or missing, use related factors, dirt accumulation, degradation by UV rays and heat wear from traffic	Y	Y	N	A	Y	N			YES	NO	CD		

Table 3-15 Bus Shelter

FF/ FM		CA			CS	PM TASK				FT	RD	PS	D	P
		1	2	3		4	5	6	7					
10A 10B	**Functional Failure** Fails to shelter passengers safely Fails to inform user independently													
	Failure Mode													
101	Damage (vandalism)	Y	N	Y	B	N	Y	N	N	YES	NO	CD	Cleaning More frequent Safety Inspection/redesign Espouse time-based upkeep	A monthly MTBI is carried out for safety inspection Yearly Interval for detailed inspection
10B1	Notifications unavailability	N	.	.	D	N	N	N	Y	NO	YES	CD		

3.6 DISCUSSION OF RESULTS

Shortage of deterrence of failure always leads to a rise in the cost and benefit ratio about both the individual maintenance intervention and a group of interventions relating to the network of infrastructure (Garozzo and Andrea, 2006). After maintenance task selection, RCM logic decision proposes various maintenance strategies that would be carried out in cyclic, routine work adapted and reactive manner. As shown in Table 3.1, FMEA of road junction asset precedes decision logic in which FMEA spots are underlying hazards, and the latter assigns a critical value which facilitates criticality class selection. It is essential to carry out a criticality analysis as it is the best way to evaluate how asset failures can impact system performance to analytically grade assets for the intention of maintenance prioritisation and reliability improvement initiatives (Ray, 2010). Before choosing criticality class for the assets, failure effects are classified as for how they affect safety and environment (A), user mission (B), other failures (C) and hidden failures (D). For example, if the failure affects the safety of road user which could lead to loss of life, then it is classified as high priority. Table 3.6 to Table 3.15 for the investigated asset presents the results of decision logic tree analysis.

The interrelationships between road junction assets have become more evident with an examination of the functional failures and maintenance strategies of different asset interconnection. For example, drainage systems in Table 3.6 functionally fail when they are unable to take excess water from carriageway and surroundings which often leads to failure of other assets such as carriageway by causing potholes which have long-term and imminent effects such as skidding with severe consequences. The maintenance strategy to remediate failure modes is captured in FMEA. The FMEA is used to identify, quantify, evaluate, and prioritise the risk associated with the assets. It helps to reduce the risk of failure by detecting the failure modes of the assets. Downtime to restore however is not consistent with the criticality of failure. For example, if it is discovered that failure of carriageway has a response time of 5 days, but the failure of drainage to take away the excess of water concurs to the standard schedule of 28 days. This information depicts that road transport network maintenance prioritisation is currently biased towards maintaining carriageway functions, but FMEA results demonstrate that the functions of other assets are distinct and significant.

This RCM analysis has facilitated an in-depth analysis of road junction asset failures particularly the procedural aspects of maintainability. In the implementation of RCM, potential failure modes and causes associated with each road asset have been identified. Consequently, the criticality class of each failure mode is calculated. The results show that road lights at Table 3.9 with criticality classes of A, A, A, B and traffic signal in Table 3.11 with A, A, D have the highest criticality. The result suggests that high priorities should be devoted to both assets during maintenance prioritisation. The RCM process has offered a rational basis to assign appropriate maintenance tasks to manage road junction asset failures effectively. About 50% of these proposed maintenance tasks are operator maintenance, which means that current inspectors of transport asset would be required to carry out much more tasks and this will require skill level upgrading. However, this will have to be managed tactically so as not to lead to increased disruption of road junction network operations.

3.7 SUMMARY

This chapter presents a study of RCM which is conducted on the critical sub-assets of a newly constructed road junction infrastructure in Nigeria. The need for road junction system infrastructure to work at an optimum performance cannot be overemphasised. No doubt this application of RCM to road junction networks has analysed failures, criticalities and has proposed different maintenance task. The results are however slightly not in line with current road junction system network for defect-related failure regulations in developing countries. However, it helps provide signposts to inform asset owners of functional failure maintenance policy direction. Road junctions are originators are often the road traffic congestion and account for high accident rate. The traditional methods of reliability assurance used in the highway industry such as reactive maintenance and routine maintenance are often inadequate to meet the round the clock usage demands of these assets. Thus, the consideration of the application of a systematic RCM process for maintaining the system function by selecting and applying practical PM tasks.

The classical RCM methodology, a type of RCM, which has a top-down, a zero-based approach for maintenance analysis, is implemented in this study. It uses an approach that critically develops and analyses thoroughly preventive and continuous maintenance strategy in a new circumstance with the environment of uncertainty and limited operating data. The CBR cycle has been applied in the RCM approach with real-time data obtained from the UK based NMMS for highway infrastructures. The implementation of the classical RCM is successful in its application of various PM policies assigned to the assets, and it shows that its application in the highway industry could reduce excessive maintenance backlog and frequent reactive maintenance by effective optimisation of its PM intervals using RCM strategy. This chapter captures the critical functional failures of the primary highway assets in an RCM analysis using a CBR methodology. While this was achieved predicting maintenance interventions for highway assets via an FMECA, quantitative judgements on the MTTR and repair response were not captured as RCM is more of a qualitative approach. Even though qualitative method tends more towards a subjective conclusion, they play the critical part in building a quantitative analysis. The classic RCM analysis results show that highway network maintenance prioritisation is currently biased towards carriageway functions failure maintenance. Carriageway has a response time of 5 days, but the failure of drainage to take away the excess of water concurs to the standard schedule of 28 days. However, FMECA results demonstrate that the functions of other assets are distinct and significant.

CHAPTER 4: RISK-BASED INSPECTION WITH CATEGORY 2 DEFECTS

4.1 INTRODUCTION INTO RISK-BASED INSPECTION (RBI)

RBI programme allows asset owners to prioritise and strategies their inspection activities based on the potential of a defect occurring against its inherent time-based inspection regimes. Structural failure of highway infrastructure poses significant maintenance and financial burden to highway authorities in the current time because of the shortage of funding leading to more reactive and emergency maintenance. However, failure defects and risk can be alleviated by applying RBI to maintenance as it categorises the optimal inspection interims before the undesirable level of risk is stretched (Washer et al., 2016). RBI is a beneficiary in the following ways:

- ❖ improves management of risk for defective systems,
- ❖ identifies the deterioration mechanism on assets,
- ❖ cost reduction by eliminating unnecessary inspections,
- ❖ identifies effective inspection/maintenance techniques,
- ❖ produces an auditable system
- ❖ identifies and mitigate risks over time ensuring regulatory compliance is achieved
- ❖ improves asset reliability and maintainability,
- ❖ optimises planned downtime and ensures compliance with regulations

Inspections and surveys for highway assets as defined by the Code of Practice for highway maintenance are divided into three categories, namely safety inspection, service inspections and conditional surveys as shown in Figure 4.1 with the focus on safety inspection for this chapter. These inspections are anticipated to identify defects with the potential to cause harm, danger or severe inconvenience to road users of the network and the community environs. An onsite inspection is conducted to identify and assess the danger of the defect, and after that based on the extent, defects are categorised into Category 1 [CAT.1] and Category 2 [CAT.2] with appropriate response time. The CAT1 defect is those where the risk involved requires an emergency repair with a repair response time of between 1 to 24hours response, while the CAT 2 undergoes planned maintenance as expressed in Figure 4.1.

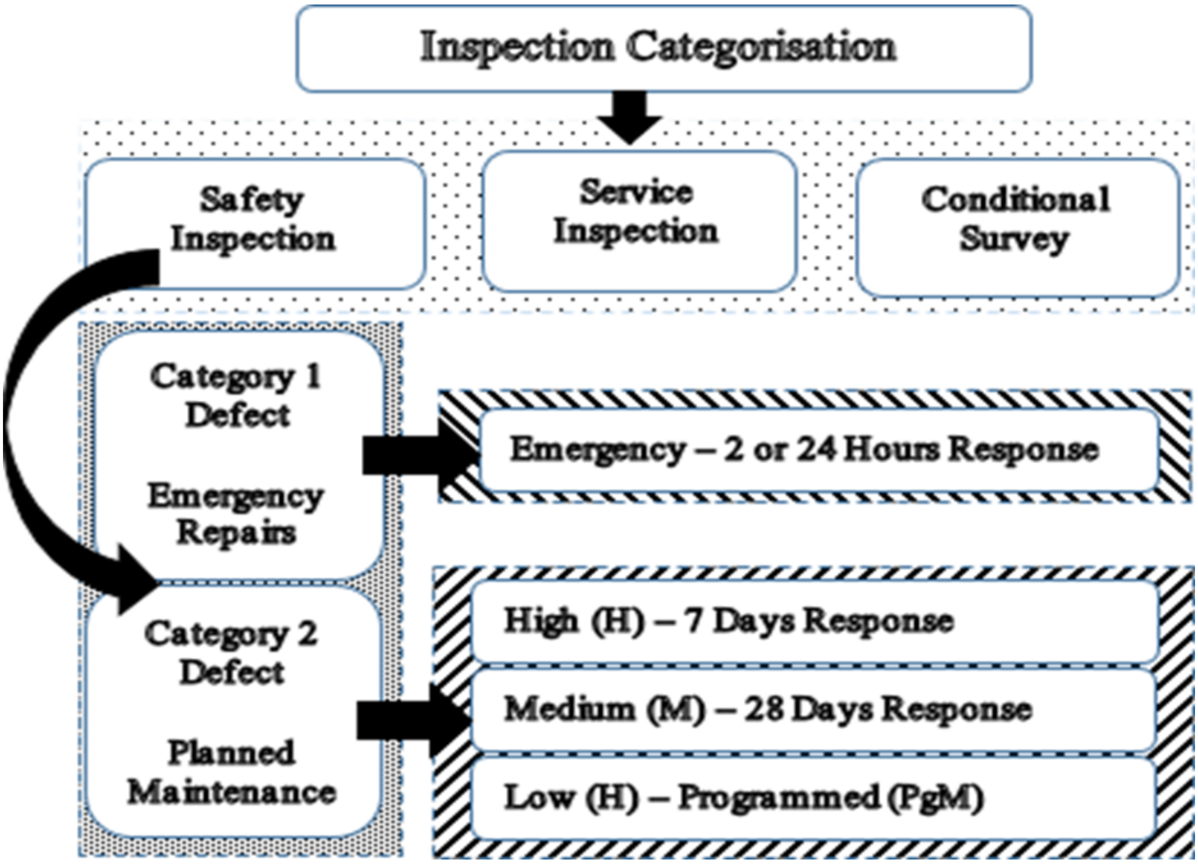

Figure 4-1 Highway Asset and Defect Classification

4.2 DEFECT PRIORITISATION FROM RISK-BASED INSPECTION (RBI)

The highway agency in the United Kingdom uses a risk-based approach for the prioritisation of the defects associated to its highway assets based on the level and types of risk associated with the hazard event that could occur from the associated defect. Having identified the level of risk that could occur, the fault is categorised as CAT 1 or CAT 2 defect. This identification approach is achievable by utilisation of six stages paraphrased as defined by (Jandu, 2008) namely

1. Define the need

2. Define the defect incident

3. Identify the likelihood/ Probability rating of the defect

4. Identify the Consequence rating of the defect

5. Identify the level of risk associated with the defect incident

6. Identify the appropriate defect category/response time for the need

4.2.1 The Consequence/Impact Analysis

The apprehended impact of the defective asset is estimated as the magnitude of the defect to the asset and the effect on the social-economic significance of the asset importance (Atkins, 2011). The defect score is based on various factors, such as defect size and impending level.

4.2.2 The Likelihood/Probability Analysis

The likelihood and probability of deterioration of the defect are used to score the defect after inspection. RBI analysis focuses on consideration of the severity of the defect and the potential failure that could arise from the defect and the assumed rate of deterioration.

4.2.3 Defect Categorisation Analysis

The defects recorded are categorised into CAT.2 (High, Medium & Low) based on the consequence and likelihood analysis in conjunction with the asset risk register for uniformity. The result from the risk impact calculated using Equation 4.1 and expressed in Table 4.1 is further used in prioritising maintenance response for maintenance timescale.

$$Risk^{Level} = Risk^{Consequence}\ x\ Risk^{Probability} \quad (4.1)$$

Table 4-1 Risk Matrix

		Probability		
		Low	Medium	High
Consequence	Low	1	2	3
	Noticeable	2	4	6
	High	3	6	9

4.2.4 Risk Assessment Framework Based on RBI-STOC Approach

The algorithm in Figure 4.2 is developed to enable a combined RBI, and Stochastic (RBI-STOC) analysis on the risk assessment for CAT.2 defects on highway assets. The RBI is conducted to identify all defects on the road network. The RBI at the onset identifies if the defect has reached a level of investigation. The investigated defect is identified as a risk if it has gotten or exceeded its investigatory level and categorised as CAT High (H), Medium (M) or Low (L). The RBI assesses all investigated hazard based on its significance with a key focus on its impact of the risk occurring, the probability of occurrence and by a standardised risk register. The impact of the hazard is happening, and the probability of occurrence is quantified on a scale of 1 to 9 in this investigation. The MTTR is obtained for various CAT.2 (H, M & L) defects.

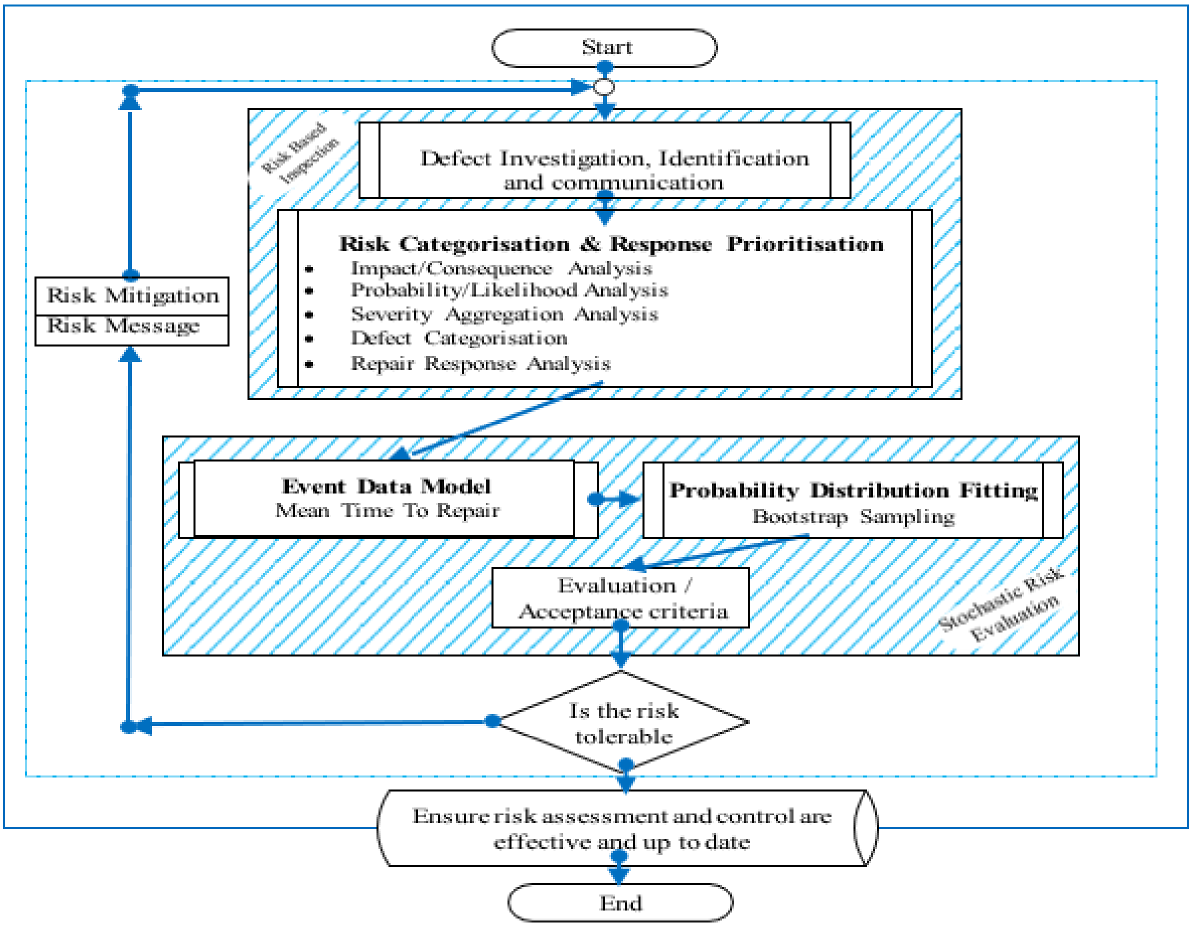

Figure 4-2 Flowchart of RBI-Stochastic Assessment Framework

The defect category is utilised in planning the repair response time for repairing of defective assets. The repair response is divided into three response time scale based on the risk level 1 to 9. A risk level at 1 indicates it is a low priority and classed the lowest impact, while nine is classed as high priority requiring fastest response time because of its high impact and probability as shown in Table 4.2. The repair response analysis is aligned to the weightings from the risk matrix with the CAT 2H having a risk weighting of 9, CAT 2M having a risk weighting of 4-6 and CAT 2L having a risk weighting of 1-3.

Table 4-2 Response Times for Repair

Defect Investigated	Risk Level	Risk Flow	Defect Priority	Standardised Maintenance Response Timescale
Risk-based Inspection	9	High	2H	7 Days
	4-6	Medium	2M	28 Days
	1-3	Low	2L	Programmed

4.3 RISK ASSESSMENT AND ANALYSIS TECHNIQUES

Techniques used in risk assessment and analysis in literature are numerous, unique and suitable for different applications. In research on risk assessment techniques at work sites by Marhavilas and Koulouriotis (2012), it was pointed out that most risk analysis is in two categories namely deterministic (quantitative & qualitative) and stochastic (statistics & forecasting). The stochastic method proposed using the classic statistic approach and the types of accident forecasting models as discussed by Marhavilas and Koulouriotis (2012) are presented in Table 4.3.

Table 4-3 Stochastic Techniques

Categories	Analysis Techniques
Classic Statistics Approach (CSA)	**Event data models** *–Mean Time To Failure (MTTF)/Mean Time To Repair (MTTR)*
	Probability Distribution - *Exponential*, *Normal, Lognormal, Weibull*
Accident Forecasting Modelling (AFM)	Time Series, Markov Chain Analysis, Grey Model, Scenario Analysis, Regression Method, Neural Networks and Bayesian Networks

4.3.1 Event Data Models

Stochastic behaviours of systems are better understood using MTTF, MTTR model as expressed in Table 4.1. The MTTF is used to describe reliability for non-repairable systems defects or failures discovered and repaired. The MTTR represents the average time required to investigate and repair the defective asset and return the asset to its proper working condition. The MTTR describes the mean of the repair time and is expressed in Equation 4.2 as discussed by Epsilon Engineer (2015).

$$MTTR = \frac{Total\ repair\ time}{Number\ of\ repair} \tag{4.2}$$

The MTTR takes the period of downtime of the system and divides it by the number of repairs recorded. The MTTR predictions commence at the replaceable/repairable unit level, where a defective unit is repaired or removed and replaced to bring the asset to as good as old.

4.3.2 Probability Distribution of Repair and Maintainability

The safety and maintenance of assets and system can benefit immensely by utilisation of probability distributions from generated work site data (Marhavilas and Koulouriotis, 2012; Shafiee and Chukova, 2013; Limnios, 2007). The following probability distributions (i.e., exponential, normal and lognormal) having the capability of dealing with the reliability of structural health and safety of system discussed by ReliaSoft Corporation, (2015)

4.4 CASE STUDY: STOCHASTIC APPROACH ON INSPECTED ASSET DEFECT

Understanding of highway assets defects prioritisation involves data exploration of occurrence of three classes of CAT.2 defects developed over a period captured from real-time safety inspection data and measurement of MTTR of the inspected defects. The application of an RBI-STOC algorithm for highway defect interval can be beneficiary for newly fielded assets. Five years of real-time safety inspections conducted from 2010 to 2014 for highway assets in the UK are extracted from UK NMMS. The dataset from the NMMS consists of all key highway assets (i.e., carriageway, footway and cycle tracks, drainage, safety bollards, signs, road lightings, kerbs, hedges and trees, road markings, safety fences, boundary fences).

4.4.1 Piloted Risk-Based Safety Inspection Analysis

The analysis is achieved by subjecting the occurred defects recorded in the NMMS through an examination using an investigatory level benchmark to decide the risk level. The safety inspection data set is utilised to capture the fundamental defects from the safety inspection using the investigatory standards set out in the code of conduct (UK Roads Board, 2005). The inspection and repair data namely (defect ID, defect description, road description, defect category, defected asset, the cause of the defect, proposed repair description, type of repair,

repair date, interval meaning) is essential to conducting the analysis. The new alternative combines the proposed stochastic process (MTTR-PDF) using real-time piloted safety inspection data set.

4.4.2 Rate/ MTTR Model

The integration of maintainability elements accomplishes the workability and predictions using the MTTR. The maintainability predictions for various defective categories are determined from the logged inspection data. At the defect category level, the MTTR maintainability elements used in computing the defective period are: (i) defect inspection/investigated date and (ii) defect repair date. The following information from the NMMS safety inspection dataset is used to determine the defective assets period, for example, date of inspection, date of work order registration, creation, instruction and date of repair. The defective period is therefore calculated using Equation 4.3.

$$Def^{period}(Time\ to\ Repair) = Ins^{date} - Rep^{date} \tag{4.3}$$

where $Defperiod$ the period the asset remains defective, $Insdate$ the defects investigatory inspection date and $Repdate$ is the date the defective asset repair was completed or returned to as good as new condition.

A total of 37,125 defects sample was recorded in the NMMS database from January 2010 to December 2015 analysed. An expression of randomly listed defects in the year 2010 from the UK NMMS dataset showing the assets activity and defect codes, date of inspection and date of repair is shown in Table 4-4. In the sample shown in Table 4-4 which consists of thirty defects portraying ten defects each from the various CAT2 defects drawn from the UK NMMS dataset. The activity code describes the asset inspected while the defect code indicates the kind of defect detected. The time to repair also referred to as the defective assets period is the difference in time (days) between the defect inspection date and the defect repair date as logged into the NMMS database. The repair response timescale is the proposed time of repair for the various asset defect categorisation.

Table 4-4 Sample of random defects in the year 2010 from the UK NMMS Dataset

	CAT	Activity Code	Defect Code	Date Inspected	Date Repaired	Time to Repair (Days)	Repair Response Timescale
1	2H	FC-Footways and Cycle Tracks	BFRT-Blacktop : fretting	01-Sep-10	08-Sep-10	**8**	7 Days
2	2H	GC-GC - Hw. Drain: Gullies, Catchpit	BLOK-Blockage	06-Apr-10	12-Apr-10	**6**	7 Days
3	2H	GA-Grassed Areas	RPED - Risk to pedestrians	22-Oct-10	04-Nov-10	**13**	7 Days
4	2H	SB-Safety Bollards: Structure/Fixings	ACCD-Accident damage	05-Dec-10	07-Dec-10	**3**	7 Days
5	2H	SG-Signs: Face/Structure/Fixings	DAMG-Damaged	19-May-10	24-May-10	**5**	7 Days
6	2H	SL-Road Lighting: Lamp Failures	LAMP - Lamp failure	13-Jul-10	15-Jul-10	**3**	7 Days
7	2H	SS-Signs: Lamp Failures	LPO1 - Lamp Out 1	28-Jun-10	29-Jun-10	**2**	7 Days
8	2H	HT-Hedges And Trees: General	OVER - Overgrown vegetation	30-Apr-10	06-May-10	**6**	7 Days
9	2H	KC-Kerbs,Edging,Preformed Channels	CHAL-Kerb block alignment	06-Aug-10	12-Aug-10	**7**	7 Days
10	2H	CG-Covers,Gratings,Frames,Boxes	BLOK-Blockage	05-Oct-10	14-Oct-10	**9**	7 Days
1	2M	FB-Safety Fences: Metal/Concrete	ACCD-Accident damage	10-Jun-10	02-Jul-10	**22**	28 Days
2	2M	FC-Footways and Cycle Tracks	BECK-Blacktop extensive crack	30-Jul-10	25-Aug-10	**27**	28 Days
3	2M	FS-Street Furniture	DAMN-Damaged/deformed	11-May-10	03-Jun-10	**24**	28 Days
4	2M	GA-Grassed Areas	OVER - Overgrown vegetation	19-Oct-10	10-Nov-10	**23**	28 Days
5	2M	GC-GC - Hw. Drain: Gullies, Catchpit	IRLD - Rocking under load	25-Nov-10	16-Dec-10	**21**	28 Days
6	2M	RM-Road Markings	MISS - Missing	29-Sep-10	22-Oct-10	**23**	28 Days
7	2M	SB-Safety Bollards: Structure/Fixings	LAMP - Lamp failure	30-Aug-10	13-Sep-10	**15**	28 Days
8	2M	SG-Signs: Face/Structure/Fixings	SFCO - Surface Corrosion	08-Nov-10	16-Dec-10	**38**	28 Days
9	2M	SL-Road Lighting: Lamp Failures	GRGE-Graffiti General	19-Oct-10	02-Nov-10	**15**	28 Days
10	2M	SS-Signs: Lamp Failures	LAMP - Lamp failure	27-Jul-10	18-Aug-10	**22**	28 Days
1	2L	FC-Footways and Cycle Tracks	SLPF - Slab profile: uneven	29-Jun-10	16-Aug-10	**48**	Programme
2	2L	GA-Grassed Areas	PEST - Pests	18-Jun-10	03-Mar-11	**258**	Programme
3	2L	PR-Pump Rooms	PUMP - Pump malfunction	09-Nov-10	11-May-11	**183**	Programme
4	2L	RM-Road Markings	WEAR - Wear	14-Jul-10	06-Sep-10	**54**	Programme
5	2L	SB-Safety Bollards: Structure/Fixings	DAMM-Damaged/deformed	30-Apr-10	14-Jun-10	**45**	Programme
6	2L	SG-Signs: Face/Structure/Fixings	OBSG - Obscured Sign	30-Apr-10	07-Jul-10	**69**	Programme
7	2L	SL-Road Lighting: Lamp Failures	LPO6 - Lamp Out 4	20-Jun-10	17-Aug-10	**59**	Programme
8	2L	HT-Hedges And Trees: General	DBRA-Dying/dead branch	19-Nov-10	18-Feb-11	**92**	Programme
9	2L	MC-Minor Carriageway Repairs	LODT-Local edge deteriorate	10-Jun-10	09-Nov-10	**152**	Programme
10	2L	BT-Boundary Fences: Timber	ACCD-Accident damage	26-Nov-10	04-Jan-11	**40**	Programme

Note: 2H, 2M and 2L represents Category 2 Defects High, Medium and Low respectively

The average MTTR interval for CAT.2 defects of the complete fielded UK NMMS dataset is calculated, and its interval means and standard deviation for all three classes of CAT.2 defects are illustrated in Table 4.5. The intervals mean represents the average repair for different defect categories. The defective period for various CAT.2 defects from the data set is calculated and the average MTTR interval days currently in use: CAT.2H ≈ 11 days, CAT.2M, ≈ 42 days and CAT.2L ≈ 97 days as shown in Figure 4.3.

Table 4-5 Statistical references for Category 2 Defects of UK NMMS dataset

Defect Classification	**No of Defects N**	**Mean** μ'	**StDev** σ'	**Median**
CAT.2H Defect period	10807	10.842	27.600	3.058
CAT.2M Defect period	22146	41.814	50.954	24.473
CAT.2L Defect period	4172	97.22	97.16	63.68

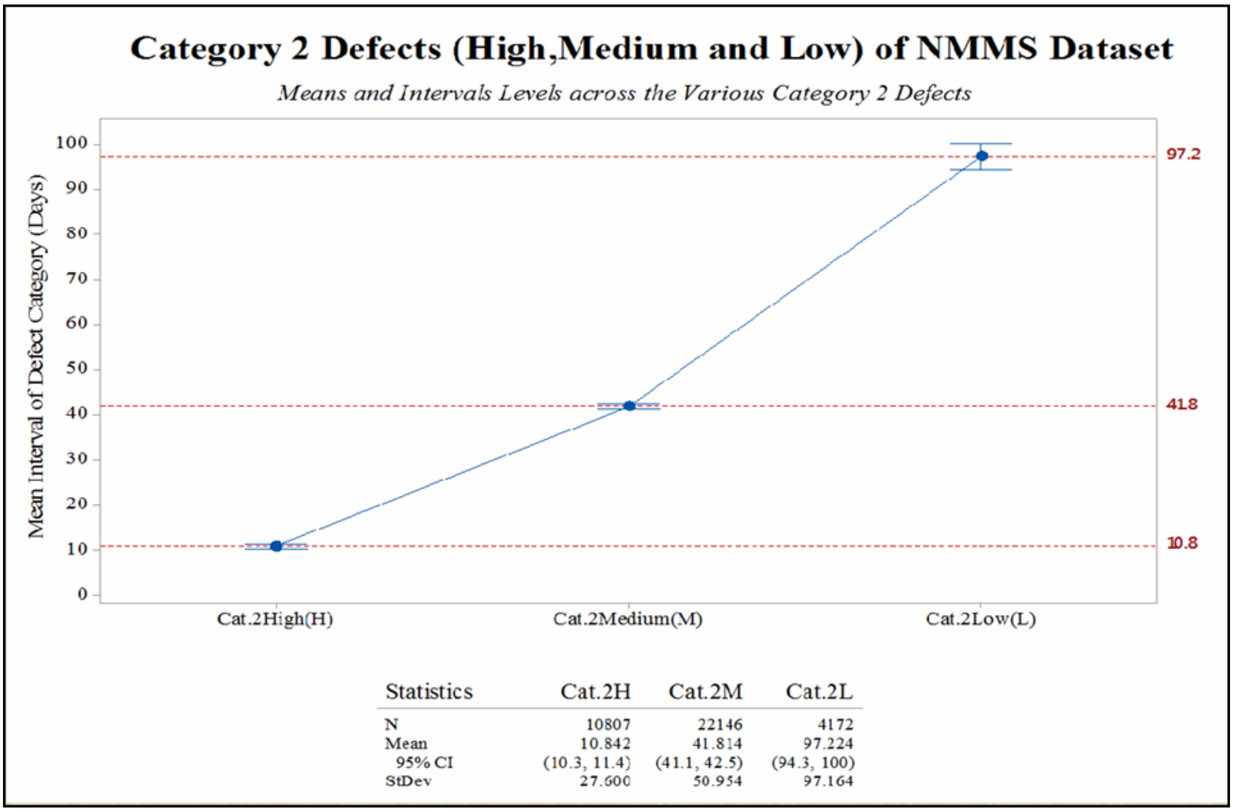

Figure 4-3 Piloted NMMS Category 2 Assets Defect Inspection

4.4.3 Bootstrapping Sampling Simulation of the Piloted Defect Inspection

Bootstrap sampling is considered as a type of Monte Carlo method since it uses random sampling. Bootstrapping is a method that estimates the sampling distribution by taking multiple samples with replacement from a single random sample. These repeated samples are called resamples. Each resamples is the same size as the defects sample was recorded in the NMMS database from January 2010 to December 2015 analysed. It is used to understand the impact of risk and uncertainties by running multiple trial runs, called sampling using random variables. The sampling is the process of running the model with an aim to obtain numerical results, numerous times with a random selection from the input distribution for each variable. A sampling distribution describes the likelihood of obtaining each possible value of a statistic from a random sample of a population; in other words, what proportion of all random samples of that size will give that value. The bootstrap distribution of a statistic, based on the resamples, represents the sampling distribution of the statistic

Probability distributions are a fundamental concept in statistics and are beneficiary both at a theoretical and practical level. The mean μ and standard deviation σ generated from MTTR interval from the sampled safety inspection data set is sampled to derive the best-fit distribution trend of each defect category. The resulting dataset is simulated via a 1000 parametric bootstrap sampling using a 95% confidence interval level. The best-fit distribution is generated using the most precise interval μ and σ, predicting the most current MTTR interval for the various defect categories. The defects sample represents the population from which it was drawn. Therefore, the resamples from this defects sample represent what we would get if we took many samples from the population. The sampled bootstrap distribution using @RISK by palisade cooperation redefines the MTTR interval slightly and portrays their ideal distributions as follows: CAT.2H: ≈ nine days lognormal distribution, CAT.2M: ≈ 43 days lognormal distribution and CAT.2L: ≈ 97 days exponential distribution as presented in Figures 4.4, 4.5 and 4.6.

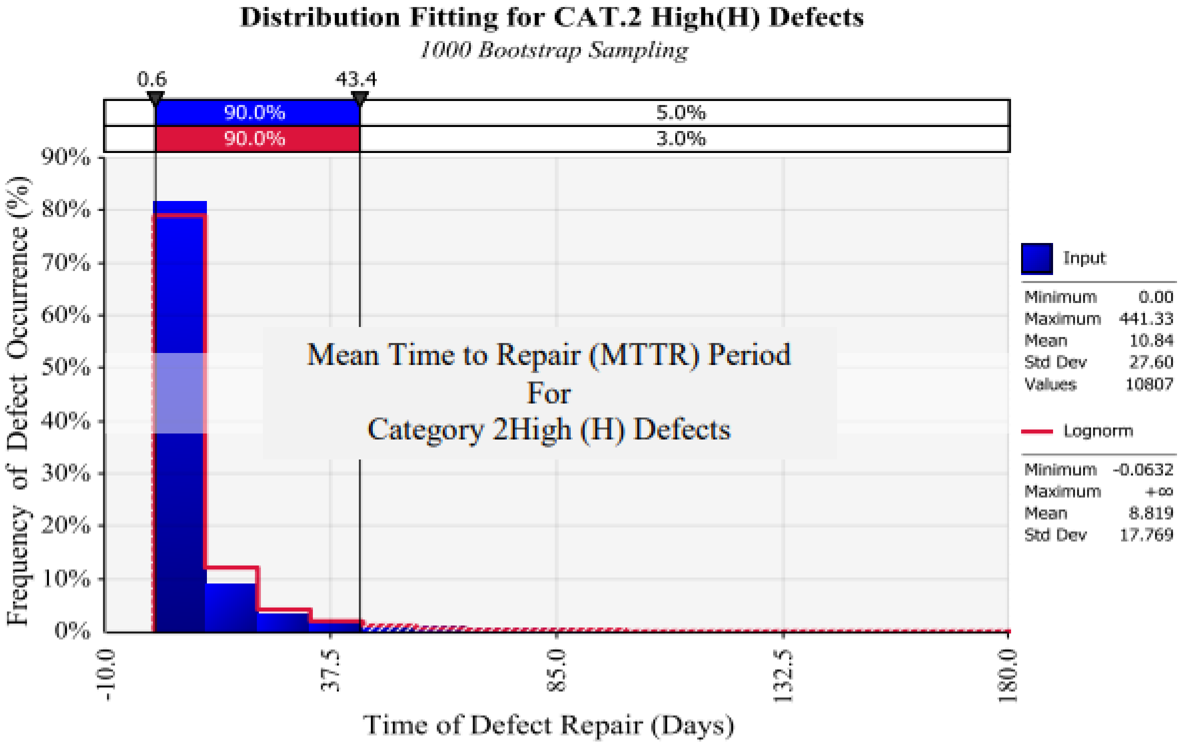

Figure 4-4 Parametric Bootstrap Sampling of PDF of CAT.2 High Repair Interval

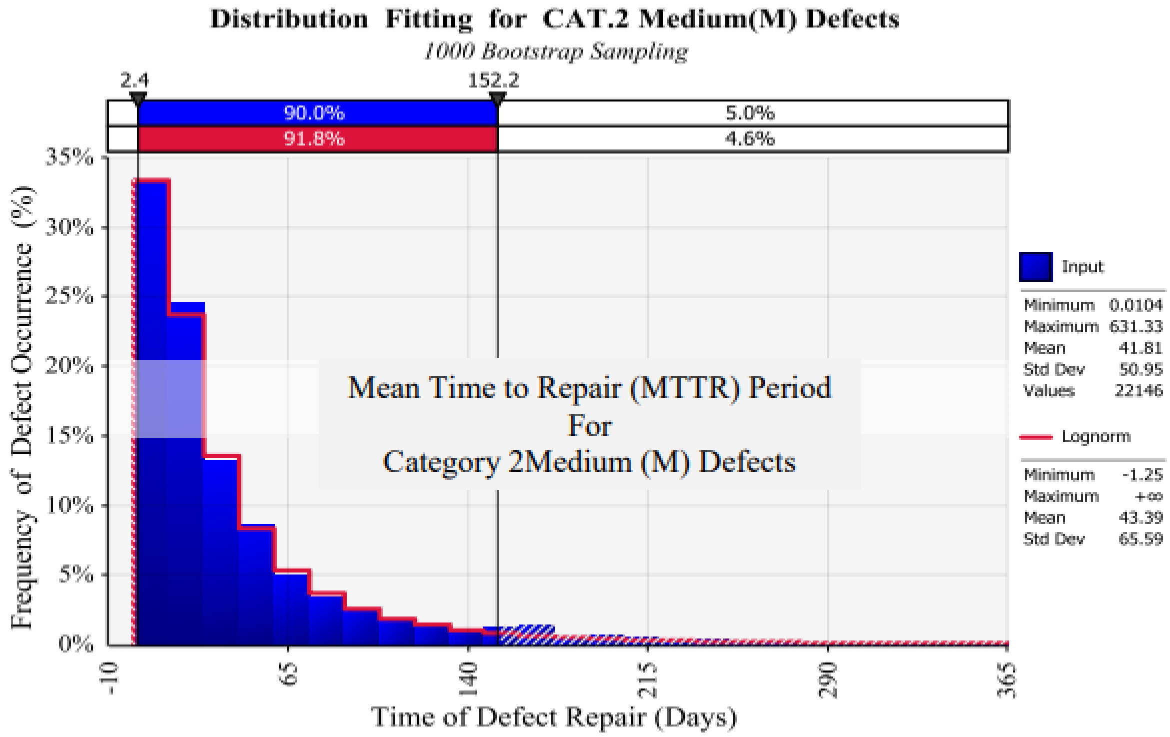

Figure 4-5 Parametric Bootstrap Sampling of PDF of CAT.2 Medium Repair Interval

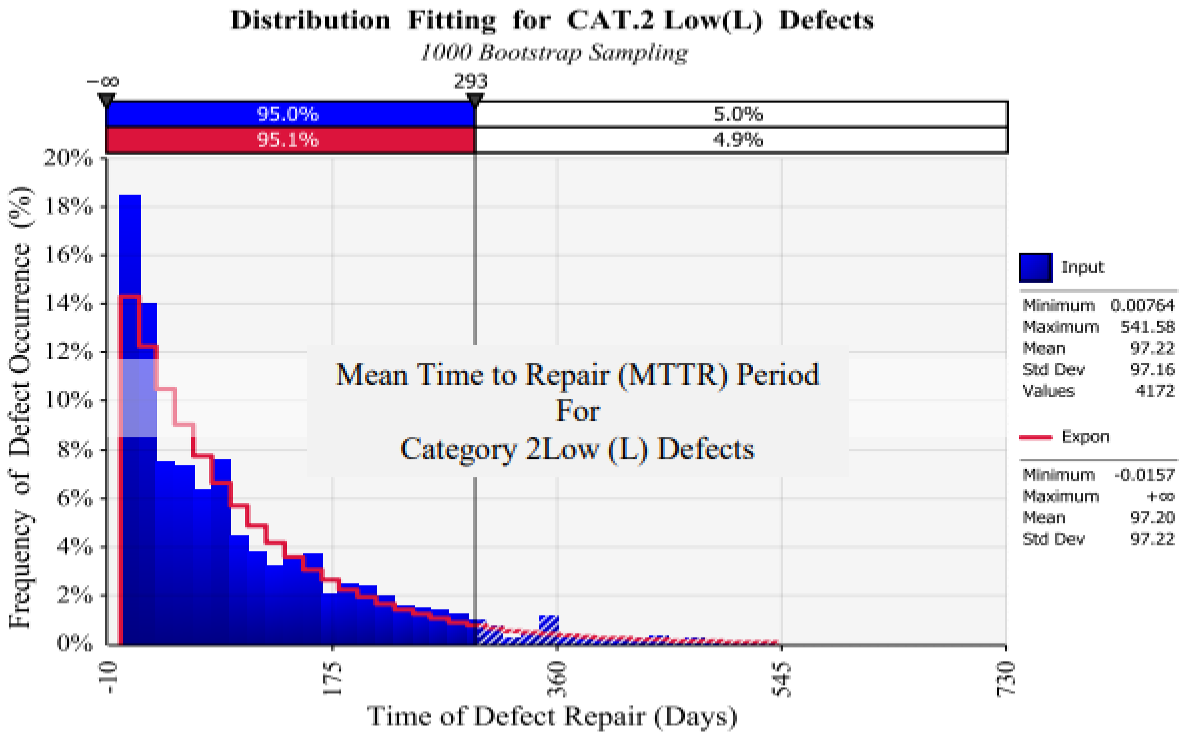

Figure 4-6 Parametric Bootstrap Sampling of PDF of CAT.2 Low Repair Interval

To create a bootstrap distribution, many resamples are taken. The results above in Figures 4.4, 4.5 and 4.6 portrays an estimate of the sampling distribution of the proportion of input means which represents the MTTR. The following histogram shows the bootstrap distribution for 1,000 resamples of the original mean. Repeated sampling with replacement from the piloted defect inspection means from Figure 4.3 mimics what the population might appear to be. Because sampling with replacement does the resample, the bootstrap sample proportion will usually not precisely match the original proportion. The blue bar chart in Figures 4.4 shows the original sample found that the mean is 10.84, while the bootstrap sample found that the mean is approximately 8.819 for the CAT.2H having an exponential distribution as it's best-fit. The blue bar chart in Figures 4.5 shows the original sample found that the mean is 41.81, while the bootstrap sample found that the mean is approximately 43.39 for the CAT.2M having n lognormal distribution as it's best-fit. The blue bar chart in Figures 4.6 shows the original sample found that the mean is 97.22, while the bootstrap sample found that the mean is approximately 97.20 for the CAT.2M having an exponential distribution as it's best-fit.

4.4.4 Joint Evaluation of RBI-STOC Procedure

The MTTR maintenance interval outcomes of the defective periods about the defect categories based on the RBI and STOC analysis are presented in Table 4.6. The precise MTTR intervals generated via the probability distribution using a bootstrap sampling proposes the recommended MTTR interval in Table 4.6. The MTTR and PDF provide better inspection interval regimes in consideration of the results from the MTTR-PDF outcomes.

Table 4-6 Appending Safety Inspection for Highway Asset Defect Categories

Priority	**Risk Level**	**Present Repair Response (Days)**	**Resultant Stochastic Interval (Days)**		**Proposed RBI Regime**
			MTTR	Best-Fit PDF	
2H	9-15	7Days	10Days	8Days Lognormal	Decrease
2M	4-8	28Days	41Days	43Days Lognormal	Decrease
2L	1-3	Programme	97Days	97Days Exponential	Maintain

4.5 SUMMARY

This chapter presents a study piloted on highway assets CAT 2 defects. An RBI and Stochastic (STOC) technique for identifying suitable inspection interval for highway assets CAT 2 defects based on similitude from RBI are projected. The connection of quantitative risk analysis to maintenance has not been effusively studied. Also, there is an absence of systemic, RBM methodologies that can solve the problems facing the highway agency maintenance programme. The inspection and maintenance strategy for highway infrastructure requires continuous improvements to reduce the high occurrence of defective highway assets. Combined RBI and stochastic (STOC) techniques are considered in this investigation to give an in-depth understanding of highway asset maintenance response. Appropriate data information is extracted from NMMS and complementary information elicited from maintenance experts as well as recommended standards.

Safety inspections piloted within 5 years is evaluated using the projected RBI-STOC approach. The RBI incorporates the consequences and likelihood of the defects, and the combined STOC techniques utilised defines the actual maintenance interval operated. The RBI-STOC approach proposes reclassification of repair intervals of highway asset defect, appropriate maintenance task response and efficient maintenance prioritisation of highway assets in equivalence with a contribution to system average MTTR and downtime. The approach intends to enhance periodic method to inspection and maintenance regimes, to support high-reliability achievement and steady asset availability as well as to reduce downtime and hazards.

The resolution is redeemable using the RBI - STOC approach as the most common defect mechanism associated with highway assets can be assessed and inspection needs prioritised to understand and curtail the failure times of event of the assets. However, quantitative analysis of literature has been successful in the determination of failure times using point estimation, Maximum Likelihood Estimator (MLE), Least Square Estimator (LSE), and other methods in modelling failure MTTF and MTBF of systems. This area is further considered in the following chapter to be the research a compound view to support the findings from the MTTR of highway assets. The research using the RBI-STOC methods indicates that highway maintenance may need to consider reducing the safety inspection time giving to CAT2H defects and increase safety inspection time associated with CAT 2M defects as this certainly would help to reduce unwarranted callout and addressing defects at less risky. The results of the RBI-STOC methods signposts that best-fit distribution using the most precise interval μ and σ can predict the specific stochastic interval for multiple defect categories as portrayed for CAT2H, CAT2M and CAT2L than a standard MTTR about the regular repair interval in use.

CHAPTER 5: RELIABILITY GROWTH ANALYSIS AND CURVE MODELLING

5.1 INTRODUCTION

The instantaneous and cumulative effect of failure rate for repairable fielded systems depletes the reliability of road network systems. This chapter bridges the rationale and statistical techniques employed in the reliability analysis and growth curve modelling for application to carriageway with defects/failure events obtained from fielded systems. Real-time user operational data is analysed to enable preventive and predictive maintenance insight to be adapted from its growth trends and curves. Carriageway fielded population from its failure events are analysed, and models are developed using statistical assessment, parametric distribution analysis and parametric growth trend. The reliability behaviour of the failure events is evaluated using reliability estimates of its MTTF for instantaneous failure time of the event and Mean Time Between Failure (MTBF) for cumulative times of events. Growth trends and parametric growth curves of the homogeneous Poisson process (HPP) and non-homogeneous Poisson process (NHPP) of the individual and cumulative failure time of events are presented using Maximum Likelihood Estimation (MLE) and Least Square Estimation (LSE) as well as the Mean Cumulative Function (MCF) of failure time of events.

These subjects are addressed in this chapter by the use of the real-time application on carriageway asset failure times of the event, presenting their explanatory variables, estimations, and model specification. The framework of this chapter follows an introduction of the system selection of the operation data used including the overview to data selection for RGA. Section 5.2 reviews the modelling statistics for its reliability statistics, parametric distribution and parametric growth curve analysis, with emphasis on HPP and the NHPP ~ power law process. Section 5.3 is dedicated to graphical assessment using histogram and goodness for the statistical analysis, probability plots and growth curves models for the parametric analysis. In

Section 5.4, the results of the presented tabulated and graphical outputs utilised in developing the trends, curves and models are interpreted and discussed.

The selection of crucial highway asset having different functions and failure modes characteristics gives a profound understanding of the failure phenomena in general. Most functional failures of road systems arise as a result of human or mechanical causes. The carriageway road system observed for this application was carefully selected by the availability of the dataset and for more profound metamorphosis in the carriageway characteristics in field operation. Unavailability of real-time fielded data and lack of accurate data assessment are significant hindrances in reliability analysis. This challenge often leads to inappropriate decision making arising from suboptimal parameter estimation conducted (Alkali et al., 2009). Likely problems which could arise from data extractions about the maintenance activities are acknowledged and taking into consideration during data extraction from the NMMS database. The road user field operational population collected and analysed emanates from the NMMS of highway asset in the United Kingdom, since its very time consuming and expensive in generating new dataset considering the disparate systems of the road network. Highway assets portray their real characteristics when in operation, thereby making the choice of dataset appropriate for the analysis.

The availability of DfT UK NMMS failure datasets enables intensive data analysis of highway failure estimate, trends and evaluate reliability growth. The carriageway dataset sample consists of operation failure time of events is a road network in the south-east of the United Kingdom. The duration of failure time of the event of the carriageway sample analysed from the data set population spans for five years ~1825days of field time operation. Carriageway events of failure data from 1st, January 2010 to 31st, December 30th, 2014 was captured for the data study. The availability of real-time repairable data from fielded system data set from the DfT UK NMMS thus directs the analysis towards criteria for the development of reliability process for growth trends and curves. Reliability growth trends and curves are best defined and expressed by their statistical and parametric characteristics. Parametric estimates, parametric distribution and parametric growth curves attributes are essential on the development of the statistical assessments, reliability analysis and growth models using the Poisson and Power law process (Minitab Statistical Software, Minitab Inc.).

5.2 STATISTICAL ASSESSMENT OF RELIABILITY ESTIMATES AND GROWTH CURVE

5.2.1 Lifetime Distribution

Statistical probability distributions that are used in life data analysis and reliability engineering are often referred to as life distributions and are fully described by their pdf. Data observed from failure events that are obtained from the fielded system are considered as actual failure times and can be modelled by most common eleven distributions namely, normal, lognormal, 2-parameter lognormal, Weibull, 3-parameter Weibull, exponential, 2-parameter exponential, logistic, log-logistic and 3-parameter log-logistic. The expression for the exponential, normal and lognormal distribution was expressed in Chapter 4 section 4.3.2. The Weibull distribution is a universal purpose distribution used to model the strength of the material, time to failure in components and systems. The versatility of the Weibull distribution enables it to be widely used in reliability and life data analysis. The most commonly used dissemination for reliability engineering is the Weibull distribution which has the form of a 3-parameter Weibull, 2-parameter Weibull and the 1-parameter Weibull. The three-parameter Weibull pdf is as shown in Equations 5.1(ReliaSoft Corporation, 2015).

$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} e^{-\left(\frac{t-\gamma}{\eta}\right)^{\beta}} \quad (5.1)$$

where:

$$f(t) \geq 0, t \geq 0 \quad \text{Or} \quad \gamma, \beta > 0, \eta > 0, -\infty < \gamma + \infty$$

and:

ŋ is the scale parameter also known as characteristics of life, the β is the shape parameter also known as the slope and the location parameter also known as the shift parameter is denoted as γ.

The Weibull distribution can be used for a variety of life behaviours depending on the values of the parameters namely the scale parameter ŋ, the shape parameter β, and the location parameter γ. The scale parameter ŋ defines where the concentration of the distribution lies or how stretched out the distribution is. The shape of the distribution is defined by the shape parameter β. The significance of the shape parameter β in distribution is reflected in the failure rate function, reliability function and the shape of the pdf. The location parameter ŋ which could either be positive or negative defines the origin of a distribution and is primarily used to shift distribution in one direction.

5.2.2 Parametric Estimation Methods

The consistency of estimation is a necessary and essential asymptotic property. However, the consistency of parametric estimations remains unsolved satisfactory in general case (Zhang, 2017). The MLE and the LSE methods amongst other types of estimation methods are the most commonly used approaches in the estimation of population parameter for random samples (Yalç et al., 2017). The likelihood function of the MLE indicates how likely the data sample is a function of the parameter values. The desired probability distribution is the one that makes the observed data ''most likely'' which means that we are interested in finding the value of the parameter vector that maximises the likelihood function. On the other hand, the LSE is calculated by fitting a regression line to the points from a data set that has a minimal sum of the deviation squared and having its lines and data plotted in a probability plot. LSE is used for estimating parameters by minimising the squared discrepancies between observed data and their expected values. The parametric estimations of the MLE and LSE reliability comparison are considered in this analysis.

5.2.3 Goodness of Fit Measures

The measure of how far the plot points fall from the fitted line in a probability plot is obtained using the Anderson-Darling statistic. The statistical resultant is the weighted squared distance from the plot points that align to the fitted line with larger weights in the tails of the distribution. The adjusted Anderson-Darling statistic is most appropriate because of its ability to change when a different plot point is introduced statistically. The Anderson-Darling statistic with the smaller measures indicates a better fit for the distributed data. Pearson correlation coefficient. For least squares estimation, the Pearson correlation coefficient is calculated. If the distribution fits the data well, then the plot points on a probability plot will fall in a straight line. The correlation coefficient measures the strength of the linear relationship between *x* and *y* variables on a probability plot. The correlation is usually signified by *r (rho)* and utilises values from -1.0 to 1.0. Where 1.0 is a perfect positive correlation, -1.0 is a perfect negative (inverse) correlation, 0.0 is no correlation.

5.2.4 Probability Plot Point and Fitted Lines

The plot point and fitted lines are used for the estimation of percentiles for the corresponded probabilities of the sample, and the expected percentile from the distribution based on the MLE and LSE estimates respectively. The plot also denotes the confidence intervals for the percentiles. The probability plot is used in assessing if the chosen distribution fits the sample data. The best-fit of the data is the distribution with the points closer to the fitted lines. The plot points of the probability plot represent the likelihood of a failure time of an event occurring before time *t*.

5.2.5 Parametric Growth Curves

Parametric growth curves are useful in the parametric analysis of repairable systems. The reliability characteristics can be achieved using HPP or NHPP power law process in the estimation of the mean number of failures as well as the MCF.

5.2.5.1 Parametric Models

I. **Homogeneous Poisson Process (HPP):** The Poisson process of the HPP has a constant intensity function, ƛ.The intervals between failures are independent as well as having identical distributed random variables that follow an exponential distribution with mean 1/ƛ. Because the intensity function of the HPP is constant, this model is only appropriate when the intervals between failures do not systematically increase or decrease. The Poisson process is perceived as not suitable for systems that are either improving or deteriorating. (Doyen and Gaudoin, 2004; Lindqvist, 2006; Natrella, 2010).

II **Non-Homogeneous Poisson Process (NHPP):** The process can either be a power law process or exponential law process with the intensity function. The intensity function of the systems represents the rate of failures or repairs. The value of the shape β depends on whether your system in test or operation is improving, worsening, or be stable. If the $0 < \beta < 1$, then failure/repair rate is considered decreasing. Thus, the system reflects an improvement over the operational time. When the $\beta = 1$, the failure/repair rate is at a constant level. Thus, the system is operating stably over time. If $\beta > 1$, then the system failure/repair rate reflects an increasing deterioration resulting from it decreased MTBF time of the event. Using the MLE method of the NHPP model, the power law process is referred to as the AMSAA model when MLE is used, and a Duane Model with LSE is used when simulating a validation to track improvement, deterioration or stability of the system. (Doyen and Gaudoin, 2004; Lindqvist, 2006; Natrella, 2010)

5.2.5.2 Mean Cumulative Function (MCF)

The MCF portrays the average cumulative number of failures or costs overall system in the time interval of (0, *t*). The mean empirical cumulative function is a plot of the MCF based on the estimated paramedic estimates of the scale and shape. While the resultant output of the MCF produces by the NHPP can indicate an increase, stable or decreased rate of system failure, the Poisson process has a constant failure rate resulting in a straight line. Needed information on the repair behaviour of the system population is gotten by the MCF having a smooth curve in a large population (Robert B. Abernethy, 2010). However, the MCF could be used to evaluate the increase or decrease of the population repair with age, thereby revealing wonderful information and insight (ReliaSoft Corporation, 2015).

5.2.5.3 Trend Test

Exact failure time of event data is classed as right censored data. Testing of trends in inter failure times is a vital aspect of the analysis of failure time of event data for the repairable system. Event plots and TTT are possible to define the trends of inter failure times. The right censored datasets are computable with any of the three most prolific trend tests namely; MIL-Hdbk-189 (The military handbook test), Laplace and Anderson-Darling. The test based on Anderson – Darling statistic is utilised is considered most favourable in literature (Kvaløy and Lindqvist, 1998).

5.3 RELIABILITY APPLICATION AND ASSESSMENT OF CARRIAGEWAY FIELDED SAMPLE

Growth curves with the exact time of failure events are used in the reliability analysis. The real-time failure time of event obtained from user fielded operation is presented in Table 5.1.

Table 5-1 Real-Time Failure Time of Event Data from User Fielded Operation

N	Time of Event (Date)	Time of Event (Day) Individual	Times of Events (Days) Cumulative
Start	01/01/2010	0	0
1	16/07/2010	196	196
2	04/10/2010	80	276
3	24/01/2011	112	388
4	21/03/2011	56	444
5	13/06/2011	84	528
6	19/03/2012	280	808
7	03/09/2012	168	976
8	21/01/2013	140	1116
9	11/02/2013	21	1137
10	18/02/2013	7	1144
11	04/03/2013	14	1158
12	26/04/2013	53	1211
13	09/05/2013	13	1224
14	03/06/2013	25	1249
15	10/06/2013	7	1256
16	02/10/2013	114	1370
17	07/10/2013	5	1375
18	22/10/2013	15	1390
19	04/11/2013	13	1403
20	02/12/2013	28	1431
21	03/02/2014	63	1494
22	03/03/2014	28	1522
23	07/04/2014	35	1557
24	02/06/2014	56	1613
25	14/07/2014	42	1655
26	16/07/2014	2	1657
27	06/10/2014	82	1739
28	14/10/2014	8	1747
End	31/12/2014	78	1825

The N in Table 5.1 which was obtained from the NMMS population having the system population information and frequency of time of event occurrences represents the number of failure events recorded within the five years period with 01/01/2010 as the start date and to 31/12/2014 and the end date. The time of the event (day) represents the date failure date record on the NMMS database. While the time of the event (day) represents the individual time of failure event from the previous, the time of the event (days) signifies the cumulative.

5.3.1 Statistical Assessment of Carriageway Failure Times of Event (Day)

Graphs representations function in two significant ways in statistical analysis. First, graphs representations are used in the analysis of exploratory data – for perceiving the communication in a set of data sample or population and also, graphs can be used for displaying data display when the message in the data set is presented.

5.3.1.1 Histogram with Fit

Table 5.2 is obtained by computing the statistical value of the failure time of the event from user fielded operation is presented in Table 5.1. The histogram shown in Figure 5.1 indicates how the distribution of the statistical value of the failure time of the event from user fielded operation is presented in Table 5.1 is centred. The sample size (N) is the total number of observations in your data. For instance, a total of events recorded between 2010 and 2014 was 28, thus the N is 28. The sample mean is the average of the time to event measurement specified in Table 5.1. The data did not follow a symmetric, bell-shaped distribution as shown in Figure 5.1 as the mean does not occur at the peak of the distribution curve. This could be as a result that the failure time of events is not normally distributed which is expected due to different failure times. The standard deviation 66.94 is the standard deviation of all the events recorded and is an estimate of the overall variation of the time of events. The standard deviation captures all sources of systemic variation which represents the variation of the time of events that occurs on the asset over time. The fitted histogram of failure time of events shows the distribution is centred around 60 to 70 days of time to a failure event, with the mean at 62 days and the standard deviation at 67 days as represented in Table 5.2, with values ranging from 0 to 280 days failure time of the event.

Table 5-2 Statistic of Failure Time of Event Data from User Fielded Operation

Variable	**Time of Event (Day)**
Count	28
Mean	62
StDev	67
Sum	1825
Minimum	2
Median	38
Maximum	280
Mode	56

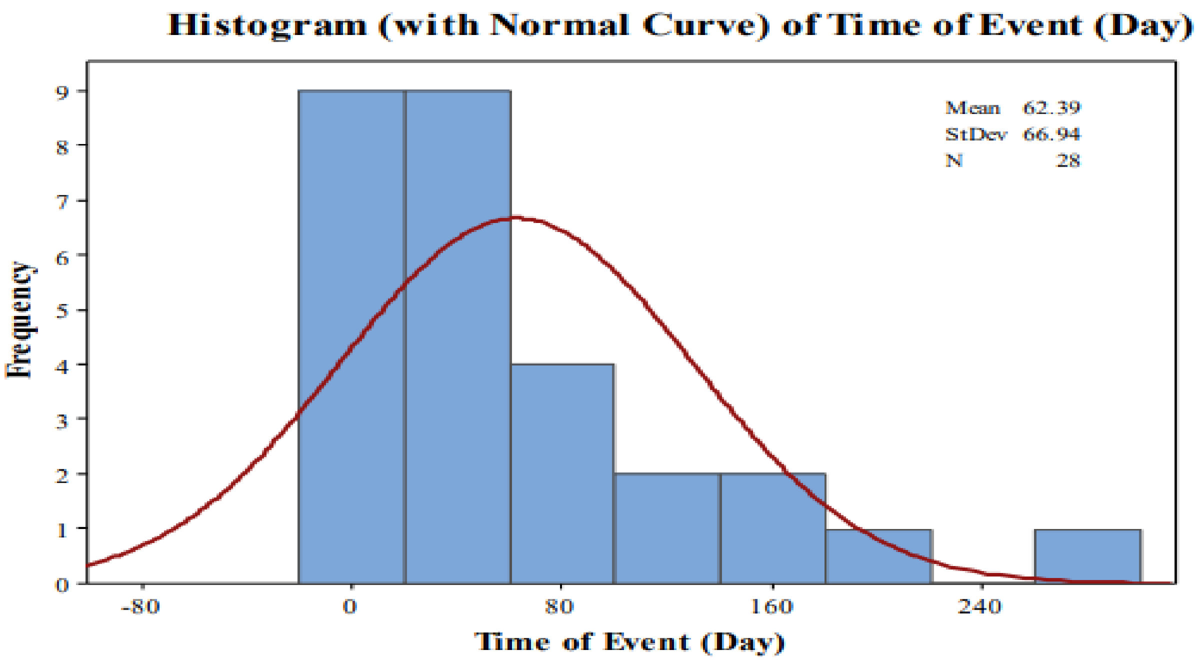

Figure 5-1 Histogram of Failure Time of Event from User Fielded Operation

5.3.2 Reliability Assessment of Carriageway Using MTTF Time of Events

5.3.2.1 Distribution Individual Plot

The introduction of fielded repairable system analysis was further instigated to specify the distribution of the UK NMMS data set. The goodness to fit and MTTF computed from the sample data using the MLE and LSE in Table 5.3 presents the best-fit distributions and their MTTF of failure time of the event from user fielded operation is presented in Table 5.1.

Table 5-3 Individual Distribution Plot Goodness to Fit and MTTF

Distribution	**Goodness of Fit**			**(MTTF) Days**	
	MLE	**LSE**		**MLE**	**LSE**
	Anderson-Darling	**Anderson-Darling**	**Correlation Coefficient**	**MTTF**	**MTTF**
Weibull	0.201	0.308	0.993	62	52
Lognormal	0.239	0.492	0.975	71	60
Exponential	0.275	0.322	-	62	55
Log-logistic	0.267	0.869	0.955	101	64
3-Parameter Weibull	0.196	0.261	0.994	62	56
3-Parameter Lognormal	0.236	0.432	0.986	70	56
2-Parameter Exponential	0.268	0.403	-	62	56
3-Parameter Log-logistic	0.28	0.772	0.972	131	54
Smallest Extreme Value	2.756	4.018	0.838	50	56
Normal	1.718	1.529	0.935	62	56
Logistic	1.271	1.341	0.949	51	56

The 3- parameter Weibull generated the smallest Anderson-Darling statistics for both the MLE (0.196) and LSE (0.261) method. The Anderson-Darling goodness of fit values are used to determine which distribution best fits the data, so the 3-parameter Weibull distributions would be a good selection when conducting the parametric distribution analysis. The MTTFs of failure time of events allow conclusions to alternate with the different distributions. The lowest MTTF for the failure time of the event is 50Days of a normal distribution using the MLE and 52 days of a Weibull distribution using LSE. The parametric distribution plot is presented in Figure 5.2 for the MLE method and Figure 5.3 for the LSE method giving a visual assessment of the point of the probability plots in the multiplets. The distribution of the smallest Anderson-Darling statistic was the three parameters Weibull distribution MLE/LSE, thus supporting a conclusion that the three-parameter Weibull distribution provides the best fit.

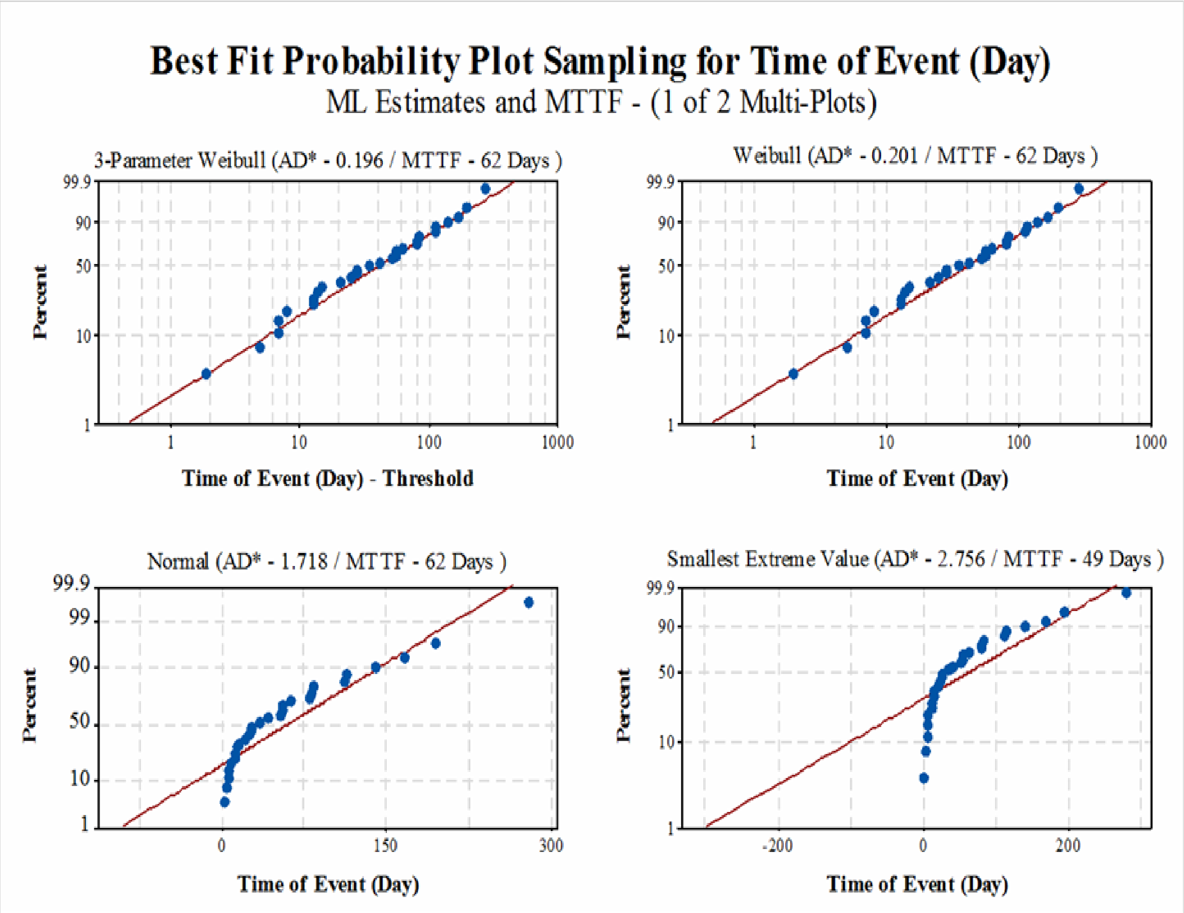

Figure 5-2 ML Estimates and MTTF Probability Plot Sampling for Best-Fit

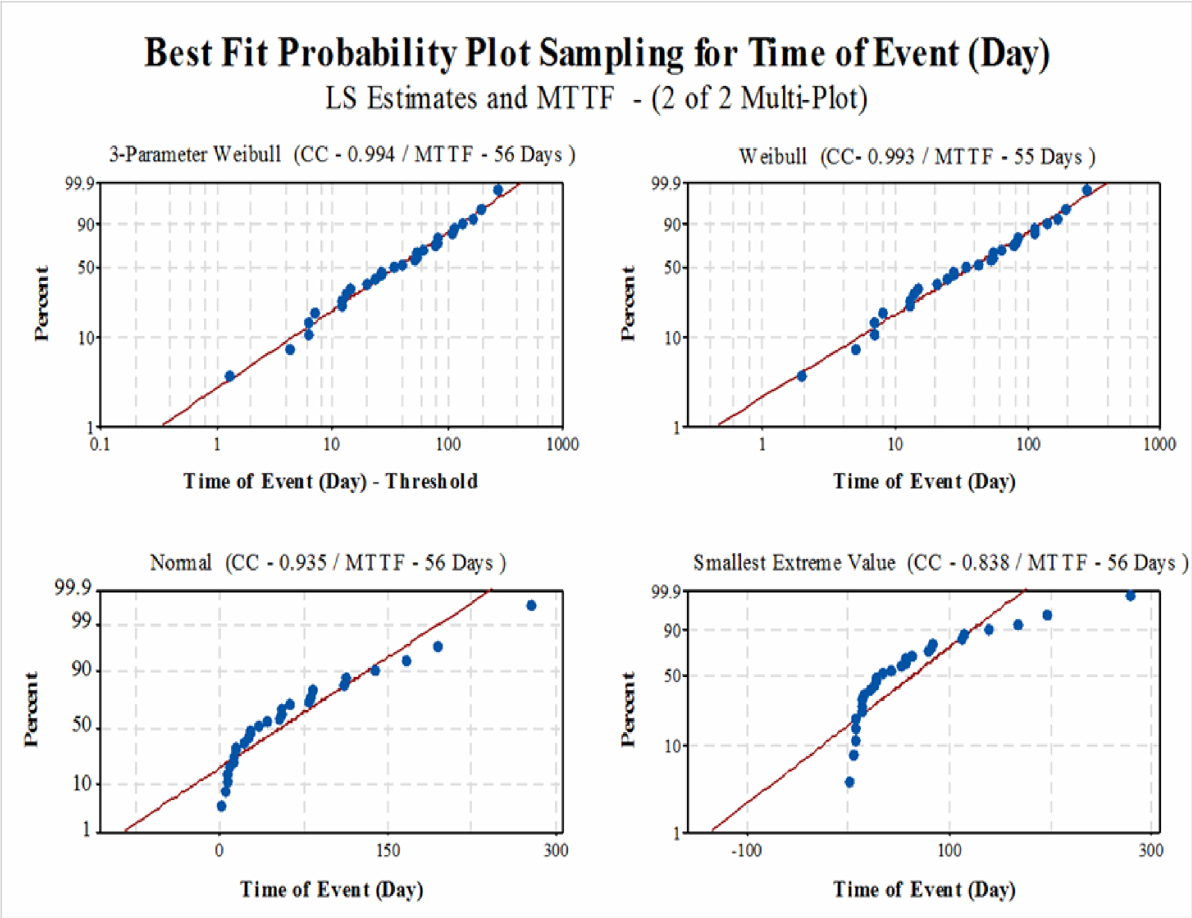

Figure 5-3 LS Estimates and MTTF Probability Plot Sampling for Best-Fit

5.3.2.2 Parametric Distribution Analysis Plot

Parametric distribution analysis of the best fits distribution is simulated using both MLE and LSE of failure time of the event from user fielded operation is presented in Table 5.1 and presented in Table 5.4. The graphical display in Figure 5.4A portrays the 3-parameters Weibull using the MLE while Figure 5.4B presents that of the LSE with both results having a 95% confidence level, with point fitted on the straight line on 3-parameter Weibull distribution.

Table 5-4 Best-Fit Distribution Parametric Estimates

Distribution	ML Estimate				LS Estimate			
			95% CI				95% CI	
	Mean	Standard Error	Lower	Upper	Mean	Standard Error	Lower	Upper
3-Parameter Weibull	62	12.37	42	92	56	10.95	38	82
Weibull	62	12.33	42	92	52	10.36	38	79
Normal	62	12.42	38	87	56	11.59	33	79
Smallest Extreme Value	50	20.40	10	90	56	11.78	33	33

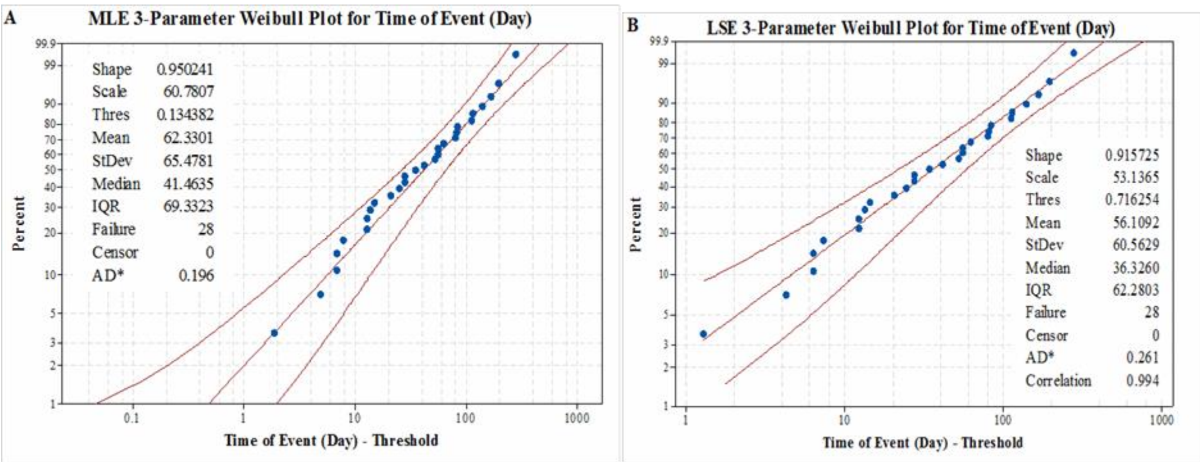

Figure 5-4 3-Parameter Weibull Plot.

A: Maximum Likelihood Estimation and B: Least Square Estimation

5.3.3 Reliability Growth Analysis of Carriageway MTBF Events (Days)

5.3.3.1 Event Plot (EP) and Total-Time-on-Test (TTT) - Field Operation - Plot

A plot of failure time of events for the fielded repairable system is shown in Figures 5.5. The plot consists of the horizontal lines, which represent the lifetime of the fielded sample. It depicts the failure events in a cross (X) points, which represent the failure times of the system. The EP in Figure 5.5A visually helps determine that successive failures events are increasing. This increment portrays a deteriorating system as the failure event represents the wear out stage of the bath curve. The Total Time of Test (TTT) plot in Figure 5.5B which represents the total time of duration the fielded operation is further used to visualise how well the models fits the data. The TTT plot provides the graphical goodness of fit test for the power law process. The power law process is considered appropriate if the TTT plot lies close to the diagonal and its curve is concave down confirming the wear out pattern of the sample system. The power law is considered adequate as it depicts a pattern, and the shifts in the curves do concave up or down but indicating steady deterioration.

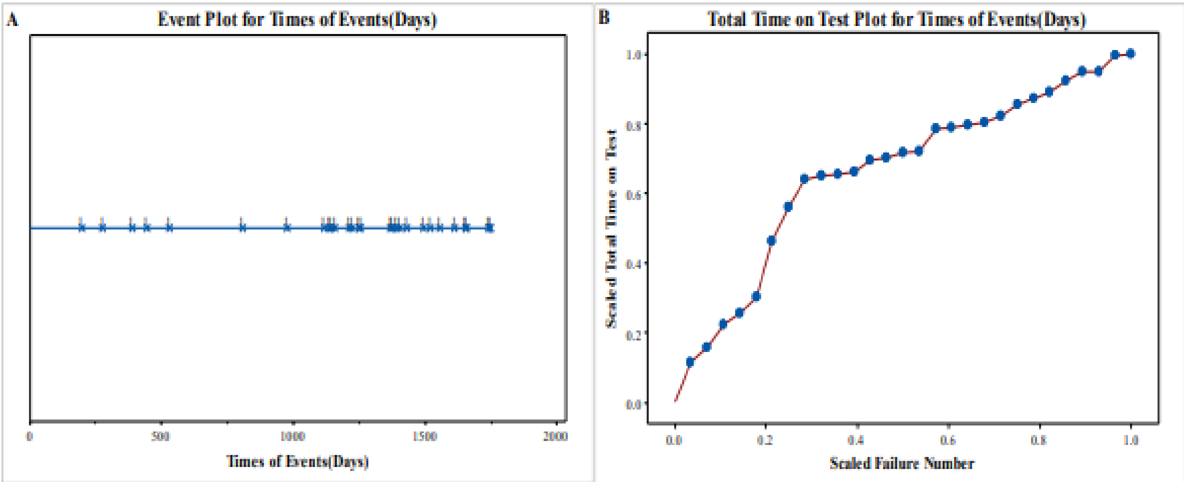

Figure 5-5 Trend Test for Failure Times of Events

A: Event Plot and B: Total Time of Test

5.3.3.2 Parametric Growth Models

Parametric growth curves are useful in performing parametric analysis for systems that are repairable. The HPP or NHPP is used for repairable system analysis in computing its mean number of failure time of events for the rate of occurrence of a failure. Parametric estimates with standard error and confidence limit for the failure times of events (cumulative) of the HPP and NHPP growth curves are computed and presented in Table 5.5.

Table 5-5 HPP and NHPP Growth Curve Models Parametric Estimates

Growth Curve Model	**Parameter**	**ML Estimate**				**LS Estimate**
		Estimate	**Standard Error**	**95% CI**		**Estimate**
				Lower	Upper	
NHPP	Shape	1.96	0.364	1.36	2.8203	1.43
	Scale	319	105.8	166	611.37	193
HPP	MTBF (Days)	62	11.79	43.1	90.364	92.8

The power law process of the NHPP model simulated can be portrayed as an AMSAA or Duane model shown in Figures 5.6(A-D) depending on the parametric estimation used. The power law plot replicates the behaviour of a scatterplot having a cumulative number of failures at a particular time divided by the time (cumulative failure rate) versus time. These growth models compute the sampling to see if it best-fit in a power law process or a Poisson process. The growth curves models can also help determine system behaviour. The fitted lines plot indicates the best-fitted line when modelling the time of failure events. This hypothesis is valid and called a Duane plot for the power law process when the shape and scale are estimated using the LSE method. The use of MLE parametric estimate redefines the model as the AMSAA model. The Duane plot indicates a linear slope in confirming the appropriateness of the chosen model. Both the AMSAA and the Duane model of power law models as shown in Figures 5.6 A and B indicates that reliability deterioration of the system is failing by the representation of a positive slope indicating reliability deterioration. Although both models indicate reliability deterioration, the AMSAA model shows a better fit to the Duane model having a scale of 0.52925 lesser than the Duane design.

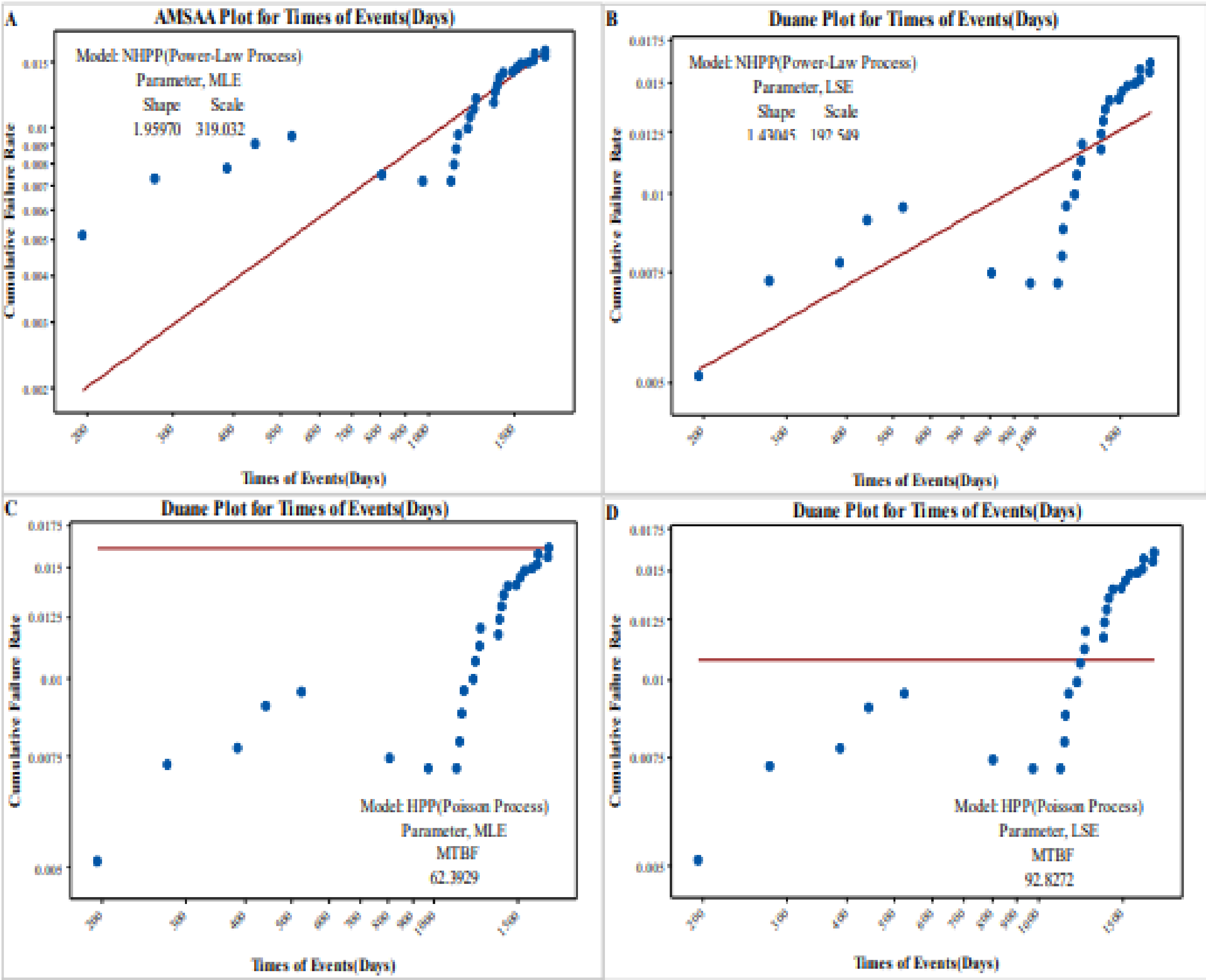

Figure 5-6 Parametric Growth Model of Times of Events

A: NHPP Power Law Process of MLE, B: NHPP Power Law Process of LSE, C: HPP Poisson Process of MLE and D: HPP Poisson Process of LSE

The HPP models are presented in Figures 5.6 C and D of the MLE and LSE respectively. The Poisson process of the HPP model is one of the underlying statistical ideas for defining the failure rate of a repairable system. On the other hand, it is only suitable for a system that does not improve or deteriorate, an assumption that is hard to meet in practice. Although the model for the Poisson process, as shown in Figures 5.6 C and D portrays a stable system (Horizontal line) which invalidates the trends of the EP and TTT. The MCFs of the failure times of event are further used to see the parametric behaviour of the cumulative mean function of the models.

5.3.3.3 The Mean Cumulative Function (MCF) of Data Showing the Trend

The MCF by the Nelson - Aalen Plot is utilised for determining if the system is improving, deteriorating, or staying constant as shown in MCF plots, in Figures 5.7 (A-D). The MCF plot provides information about the pattern of system failures. For the NHPP model application, the MCF concaves in an up pattern and is identified indicating that the time of event between failures is decreasing over time revealing that the system reliability is deteriorating.

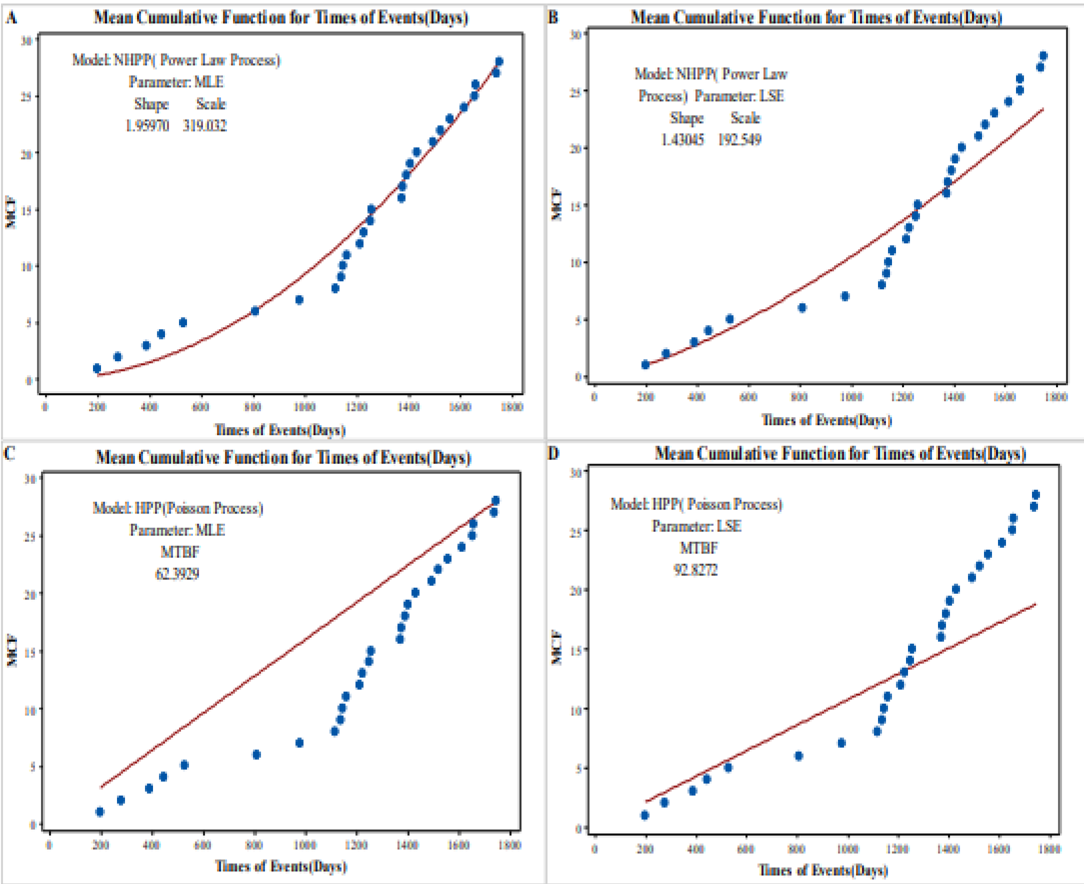

Figure 5-7 Mean Cumulative Function of Times of Events

A: NHPP Power Law Process of MLE, B: NHPP Power Law Process of LSE, C: HPP Poisson Process of MLE and D: HPP Poisson Process of LSE

The MCF plots, in Figures 5.7(A-D) shows a parametric analysis of the MCF plot of the developed NHPP and HPP using the MLE and LSE method. The parametric MCF plot is based on the estimated shape and scale in the power law process and MTBF in the Poisson process.

Both estimation methods from the NHPP power law and HPP Poisson process depicts that the trend of system failures is deteriorating. While the deterioration shows a concave pattern in the NHPP fittings in Figure 5.7A and Figure 5.7B respectively, the HPP failure rate shows constant having a resultant straight line. The output of the Nelson-Aalen plot does not depend on the model since the plot points are the same for the estimation method and model tested. However, the MCF plot differs depending on the model simulated.

5.4 DISCUSSION AND RESULTS

The reliability growth module analyses the field data by calculating scale and shape parameters that define a growth curve that fits the data. The scale and shape parameters are then used to calculate failure intensity, MTTF and MTBF. The parameters help to determine if there is an improving or worsening trend in reliability in a system. The programming fits a curve to the data according to the chosen method and displays the results graphically in the form of a cumulative number of failures plots, failure intensity plots, MTTF plots, and MTBF plots. In the analysis application reliability analysis and growth curves information was generated from carriageway failure times of events. The statistical histogram was first computed from the statistical analysis in Tables 5.1, and parametric distribution analysis was utilised in the parametric growth curves modelling distribution estimates in Tables 5.5, 5.6 and 5.7. Trend test and MCF were also used in validating the simulated results of the models developed. Figures 5.1 shows the histogram of the failure time of the event from user fielded operation from 2010 to 2014. Figures 5.3 and 5.4 are multi-plotted with a right censoring sampling of MLE and LSE portraying the least Anderson-Darling and highest correlation statistic. The parametric probability plot of the 3–parameter threshold Weibull distribution for the failure time of the event is shown in Figure 5.4A for MLE and LSE in Figure 5.4B. The 3-parameter Weibull's, the MLE (0.196 AD) in Figure 5.4A and the LSE (0.994CC) in Figure 5.4B revealed parametric probability distribution with the least AD and highest CC as computed in alignment with the mean in Table 5.3. The parametric distribution in Figure 5.4A tends to overvalue the shape (0.950241) and scale (60.7807) parameter but a smaller threshold (0.134382), while the LSE in Figure 5.4B undervalues the shape (0.915725) and scale (53.1365) parameter but a higher threshold (0.716254).

Trends test, growth curves and models for reliability analysis for repairable systems are presented in Figure 5.5 and 5.6. Figures 5.5 shows the trend test for the failure times of event also known as the cumulative effect. The trends of an EP and the TTT statistics are modelled in Figures 5.5A and 5.5B respectively. The cumulative failure time of the event from the fielded operation presented in Table 5.1 used in computing the parametric estimates in Table 5.5 is utilised in the modelling of the reliability growth patterns. A quad parametric model was developed using the NHPP MLE and LSE method for the two parametric models in Figures 5.6A and B and HPP MLE and LSE in Figures 5.6C and D. The NHPP power law process in Figures 5.6A and B confirm deterioration whereas the Poisson process in Figures 5.6C and D portrays a stable process. Although the poison process model portrays a steady deterioration due to the ability of its informative power, Figure 5.6C buttresses the best MTTF of 62days via the MLE methods makes it indisputable to ignore. Further clarification is conducted using the MCF of the models. The MCF plots in Figures 5.7(A-D) portrays the MCF of the quad parametric models using the MLE and LSE methods. The MCF Figures 5.10A and C plots confirm the NHPP power law process using the MLE method is the best model for the reliability growth curve for the fielded asset sample.

5.5 SUMMARY

The results convey that the EP and TTT plots help define the successive failure times of events. However, the instantaneous failure time of the event (MTTF) and cumulative effect of failure rate (MTBF) for repairable fielded systems on the road network depletes the reliability of road network systems as portrayed in the reliability growth curves analysis. The reliability indices indicate evidentially in twofold that not all reliability analysis confirms deterioration, firstly with evidential results from NHPP confirming deterioration whereas the HPP portrays a stable process and secondly MCF plot.

The instantaneous and cumulative effect of failure rate for repairable fielded systems on the road network depletes the reliability of road network systems. This chapter bridges the rationale and statistical techniques employed in the reliability analysis and growth curve modelling for application to road asset with defects/failure events obtained from fielded systems. Real-time user operational data was analysed to enable preventive, and predictive maintenance insight adapted from its growth trends and curves and trend be utilised for predicting prototype and right management decisions. Sample from carriageway fielded population is analysed, and models developed using statistical assessment of goodness to fit for Poisson, right censored parametric distribution analysis and parametric growth trend/curve. The reliability behaviour of the sample is evaluated using reliability estimates of it MTTF for instantaneous failure time of the event and MTBF for cumulative times of events. The growth trend and parametric growth curves of the HPP and NHPP power law are presented using MLE and LSE as well as their computed MCF of failure times of events.'

CHAPTER 6: DEGRADATION MODELLING AND LIFE EXPECTANCY

6.1 INTRODUCTION

Gap analysis in the maintenance of highway asset revealed that highway infrastructures future state and their life prediction remains one of the most demanding tasks to highway assets authorities. The modelling of defect-related deterioration from inspection surveys remains challenging due to its highway assets complex failure mechanism. In a brief retrospect on the complex structure, reliability-based inspection is considered key to achieving an optimised maintenance cost while safety and serviceability are not traded from its acceptable levels. The intricate failure mechanism and desperate deterioration trend make modelling deterioration challenging even from historical data. This challenge is addressed herein by the Linear Transition Probability (LTP) – Median Life (ML) method established, having the ability to optimise reliability and predict imminent risk from degrading highway assets.

This gap is addressed herein through the development of a linear Markov Chain model and a simulation approach to derive the future deterioration pattern without maintenance interference for carriageway. The chapter is structured as follows with Section 6.2 describing the framework of SCANNER survey inspection, Road Condition Indicator (RCI) and parameters. Section 6.3 discusses the associated literature on Markov Chain theory and linear rate deterioration analysis. It presents the method using linear Markov Chain model for forecasting future deterioration trend of asset inspection. Case study analysis using the automated results from the SCANNER survey is presented in Section 6.4. Detailed findings are discussed based on the case study. Finally, Section 6.5 summarises the concluding remarks of this chapter.

6.2 INSPECTION OF CARRIAGEWAY STRUCTURES

The importance of an accurate understanding and efficient use of structural monitoring data of road condition is very paramount to every asset manager and highway engineer. A report on the reliability of bridge assessment-based monitoring by Frangopol, Lin and Estes (1997), states that although frequent interventions planning for new and existing structures are utilised in the maintenance and repair of structures, reliability assessment and predicting models have suffered from the efficient use of SHM data. Highway infrastructure requires knowledge of its condition for timely and appropriate maintenance that will decrease adverse risk effect to road users, reduce further deterioration and the asset whole life cycle cost (Transport Research Laboratory, 2011; Department for Transport and Highway Agency, 2014). In a report on asset management for public entities by Aotearoa (2010), it is stated that restoration and even extension of an asset life are achievable by the application of planned maintenance as illustrated by a carriageway deterioration model depicted in Figure 6.1. The understanding of current asset condition and predicted future condition would give asset managers the ability to keep its assets at a steady state optimum level.

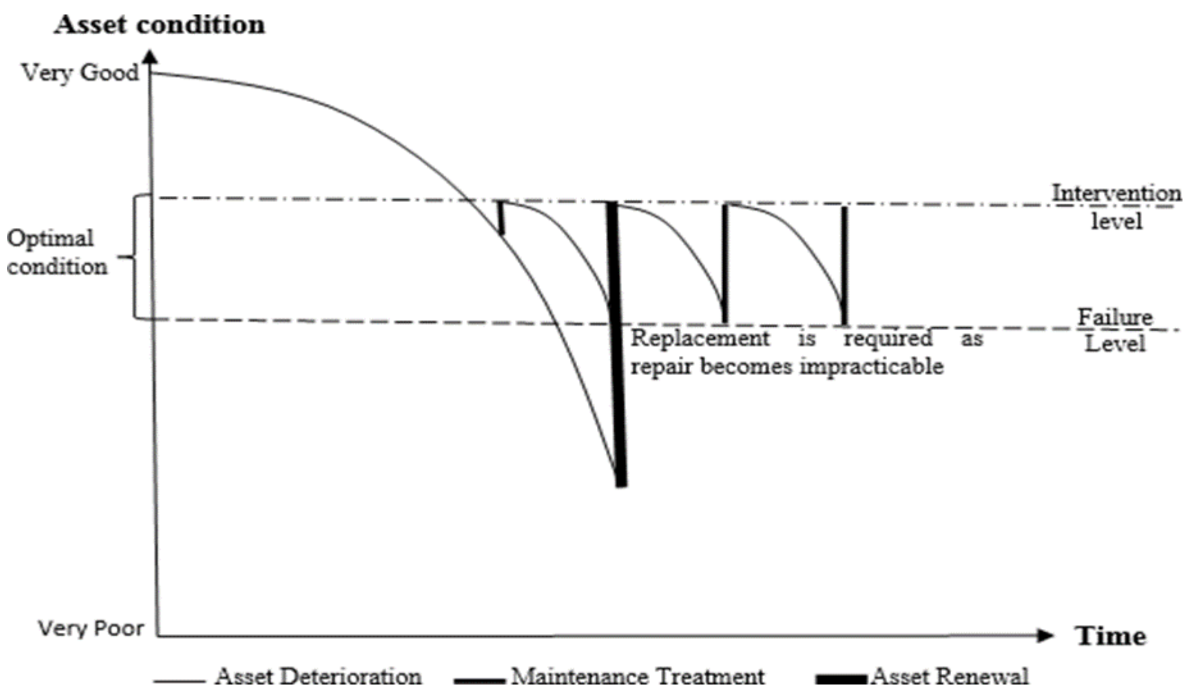

Figure 6-1A Carriageway Deterioration Model

Adapted: (Aotearoa, 2010)

In achieving accurate measurement, automated condition surveys are currently introduced for assessment of highway infrastructure worldwide. The use of Surface Condition Assessment of National Network of Roads (SCANNER) survey is considered for this analysis because it has a high level of accuracy due to its automated generated results. SCANNER surveys collect different measurements, processes them and produce “parameters” that describe the condition of the road surface. The study utilises the carriageway defect parameters classification, which is outlined in Table 6.1 as specified by the Transport Research Laboratory (2011) for the carriageway deterioration prediction.

Table 6-1 UKPMS Codes for SCANNER Survey Parameters

UKPMS Code	**SCANNER Survey Parameter**
Ride quality (LV3)	3m Moving Average Longitudinal Profile Variance
Ride quality (LV10)	10m Moving Average Longitudinal Profile Variance
Rut depth (LLRD)	Average rut depth measured in the nearside (left) wheel path
Rut depth (LRRD)	Average rut depth measured in the offside (right) wheel path
Cracking (LTRC)	The whole carriageway cracking intensity
Texture (LLTX)	Average texture depth measured in the nearside (left) wheel track

The SCANNER survey RCI was developed by (McRobbie, 2007) as discussed by (Transport Research Laboratory, 2011) to assist in characterising the condition of the road carriageway identifying lengths where the condition is poor and enabling their status to be summarised and ranked. The RCI is used to summarise the overall condition of part or all of a road network with a focus on

i. To identify lengths of road where the condition has deteriorated and the level of service that has also been worsened.

ii. To review the status of a section or length within a network.

iii. To identify the type or types of treatment required for a length of the road.

iv. To recapitulate the overall condition of a road network so that some value can be ascribed to the network.

v. To abridge the overall state of a road network, so that comparisons can be drawn between different areas.

vi. To encapsulate the overall situation of a road network, so that yearly observation of trends in condition is known.

The observations between inspection periods help support comparisons between the different areas and trends of the asset condition change. Each parameter is scored between thresholds to obtain an RCI from the condition survey. A lower threshold implies there is no need to consider maintenance and an upper threshold where further deterioration does not increase the score. The score increases linearly between the lower and upper threshold from zero at the bottom threshold to 100 at the highest. Figure 6.2 demonstrates the expression for the ride quality (LV3) defect parameter and a presentation of the various defect parameters illustrating the lower and upper thresholds presented in Table 6.2.

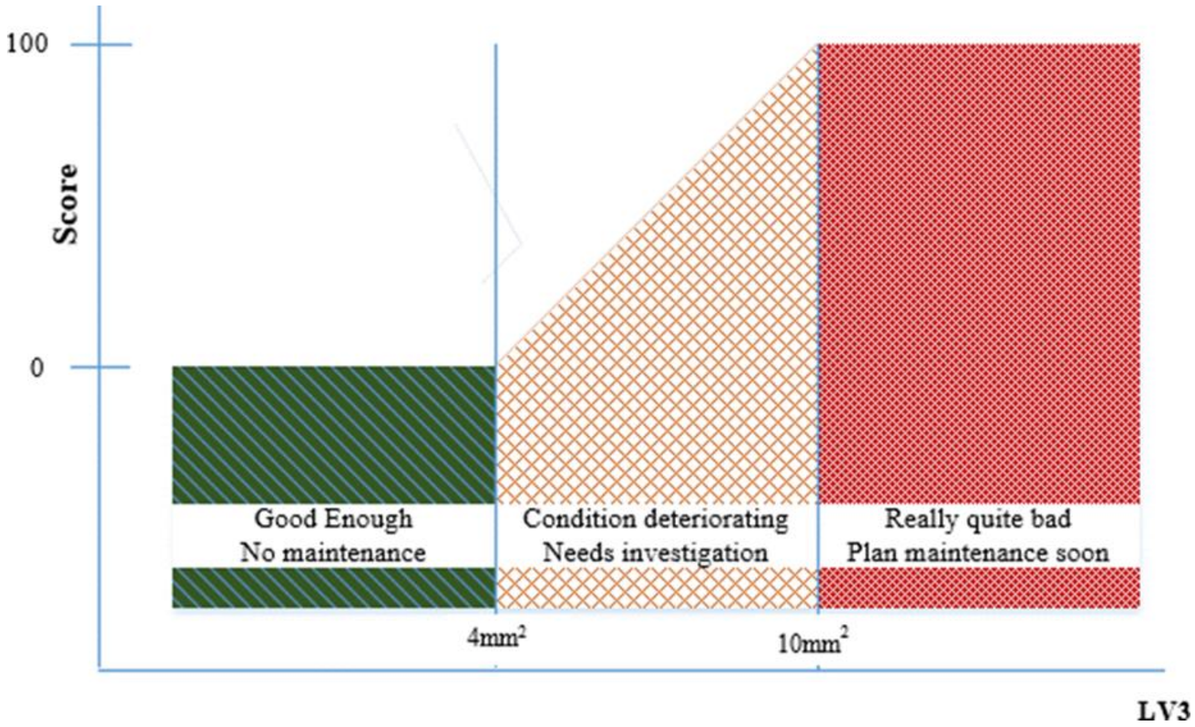

Figure 6-2 Example Scoring a SCANNER Parameter – Ride Quality (LV3)

Adapted :(Transport Research Laboratory, 2011)

Table 6-2 SCANNER Road Condition Indicator (RCI)

Parameter Thresholds and Weightings for SCANNER RCI on Principal (A) Roads		
Defects Parameter	**Lower Threshold**	**Upper Threshold**
Ride quality (LV3)	4 mm^2	10 mm^2
Ride quality (LV10)	21 mm^2	56 mm^2
Rut depth (LLRD)	10 mm	20 mm
Rut depth (LRRD)	10 mm	20 mm
Cracking (LTRC)	0.15%	2%
Texture (LLTX)	0.6mm	0.3mm

6.3 MARKOVIAN CHAIN DETERIORATION PREDICTION METHOD

A Markov Chain model describes, in probabilistic terms, the dynamic behaviour of certain types of systems over time. The Markovian method which is a stochastic process is governed by transition probabilities and characterised by two concepts namely; the system which indicates the condition at a given time and the transition states which govern the state changes that happen within the systems (Dindar et al., 2016). The model utilises a state distribution which describes the state of the system regarding the fraction controlled by each condition band and a transition probability matrix which describes its movement from one band to another. The central assumption in a Markov Chain model is that knowledge of the current state occupied by the process is sufficient to describe the future probabilistic behaviour of the process because the given the present, the future is independent on the past (Sigman, 2007). Another unique feature of the Markov Chain model is its ability to predict the median asset life. The Markov Chain model is developed based on probabilities derived from the SCANNER survey data in this study, and used in forecasting the future asset deterioration, enabling the estimation of the future condition trend as well as the intermediate life.

The current state or present state of the system $\{St\}$ also known as the starting state vector as represented in Equation 6.1 is required in the simulation of a Markov Chain model (Ortiz-garcía et al., 2006).

$$\{S_t\} = \{B_1, B_2, B_3, \dots, B_n\}^t \tag{6.1}$$

where $\{B_1, B_2, B_3, \dots, B_n\}^t$ its stationary distribution over time representing the determined percentage of various condition band.

The five grades utilised are (n=5), B_I, B_2, B_3, B_4, and B_5 represents the percentages of the RCI from grade B_I (Very Good), B_2 (Good), B_3 (Fair), B_4 (Poor) to grade B_5 (Very Poor). The stationary distribution for each band $\{S_tB_n\}$ is obtained from the condition survey. This is achieved, converting the state distribution to percentages via dividing each condition band estimate by the total size of the sample using Equation 6.2 and expanded in Equation 6.3

$$\{S_tB_n\} = \frac{B_n}{B_T} \tag{6.2}$$

$$B_T = \sum[B_1(VG) + B_2(G) + B_3(F) + B_4(P) + B_5(VP)] \tag{6.3}$$

Where B_n represents any condition band and B_T is the summation of the condition bands representing the asset condition vector over time t, representing the row vector constitutes of all condition band for all grades.

An asset in its excellent condition or a newly built asset without early damage which has five condition band spread can be formulated as represented in Equation 6.4.

$$\{S_t\} = \{1 \quad 0 \quad 0 \quad 0 \quad 0\}^t \tag{6.4}$$

Markov Chain is an example of the stochastic process, having a sequence of random variables, which makes it relatively easy to simulate from them. The Markov Chain takes place in discrete time and space, having a Markovian property guided by certain conditional probability statements which take S_t as the current state. With S_t representing the present state, the future state of the system is j giving that the entire history of everything as discussed in (Sigman, 2007) expressed in Equation 6.5.

$$P(S_{t+1}|S_t = i, S_{t-1} = i_{t-1}, S_{t-2} = i_{t-2}, \dots, S_0 = i_0) \tag{6.5}$$

The Markov Chain structure considers that only the most recent information is relevant as shown in Equation 6.6. It is homogenous when the probability (Pij), which is the transition probability from the state i to$j$, is independent of time. The past is not considered independent of the future, but if the Markovian property holds, then the past and the future are conditionally independent giving the present as presented in Riveros and Arredondo (2014) as expressed in Equation 6.6

$$P(S_{t+1} = j|S_n = i) = P(ij) \tag{6.6}$$

The transition probabilities P (ij) are summarised in a matrix of n states, (in which the probability in each row adds up to 1) called the transition matrix as expressed in Equation 6.7 (Riveros and Arredondo, 2014).

$$\begin{bmatrix} P_{11} & P_{12} & \cdots & P_{1n} \\ P_{21} & P_{22} & \cdots & P_{2n} \\ \vdots & \vdots & \vdots & \vdots \\ P_{n1} & 2 & \cdots & P_{nn} \end{bmatrix} \tag{6.7}$$

A system is considered in its worst state when it reaches the bottom right of the transition probability matrix, resulting in the following condition P_{nn} = 1 indicating that its deterioration is at a point of no return, and it is represented by a transition probability matrix defined for deteriorating systems as expressed in Equation 6.8 (Wightman et al., (2011).

$$P(IJ) = \begin{bmatrix} P_{11} & P_{12} & P_{13} & \cdots & P_{1n} \\ 0 & P_{22} & P_{33} & \cdots & P_{2n} \\ 0 & 0 & P_{33} & \ddots & P_{3n} \\ \vdots & \vdots & \vdots & \cdots & \vdots \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (6.8)$$

In carrying out condition assessment for a newly introduced inspection regime, the initial utilisation of linear deterioration rate is used for the early years pending the availability of deterioration information for updating and developing of model accordingly (Wightman et al., 2011). The linear transition matrix is flexible to use having an ability to define deterioration of asset and provide validations to the existing deterioration models. The United Kingdom Highways Maintenance Efficiency Programme (HMEP) welcomes the utilisation of Markov Chain model as this approach allows the deterioration model to be decoupled which allows users the opportunity to see deterioration as a curve (Highway Maintenance Efficiency Programme, 2012b). The transition matrix for a typical linear deterioration model as demonstrated in Wightman et al., (2011) as presented in Equation 6.9.

$$P = \begin{bmatrix} 1-\left[\frac{b-1}{E}\right] & (b-1)/E & 0 & 0 & 0 \\ 0 & 1-\left[\frac{b-1}{E}\right] & (b-1)/E & 0 & 0 \\ 0 & 0 & 1-\left[\frac{b-1}{E}\right] & (b-1)/E & 0 \\ 0 & 0 & 0 & 1-\left[\frac{b-1}{E}\right] & (b-1)/E \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (6.9)$$

where b represents number spread of the asset condition band and E is the estimated life of the inspected asset.

The value of the generic linear probability transition matrix is set in Equation 6.9, where b is set at 5 intended for a five state condition bands (VG, G, F, VP, P) and the estimated lifetime

E in years is set at an estimated age period of 16years. Hence, the probability transition matrix is conveyed as presented in Equation 6.10.

$$P(IJ) = \begin{bmatrix} 0.75 & 0.25 & 0 & 0 & 0 \\ 0 & 0.75 & 0.25 & 0 & 0 \\ 0 & 0 & 0.75 & 0.25 & 0 \\ 0 & 0 & 0 & 0.75 & 0.25 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{6.10}$$

In concluding on the Markov Chain model process, a typical transition probability matrix which constitutes the state condition and the transition matrix is presented as Equation 6.11. The nth step transition probabilities vector is a repetition of the process and is given by the following Equation 6.12.

$$\{S_{t+1}\} = [P]\ X\ \{S_t\} \quad .. \tag{6.11}$$

$$\{S_{t+1}\} = [P]\ X\ \{S_t\}^n \tag{6.12}$$

where $\{S_{t+1}\}$ the one-step is transition probability and $[P]$ is the transition probability matrix, $\{S_t\}$ is the current state vector and $\{S_n\}$ is the nth step transition probabilities.

It is likely that an asset starting at any condition state will deteriorate following the transition probability matrix until it reaches a state that further deterioration becomes futile. The period when a fraction of the failed state reaches 50% ~ 0.5 can be used to estimate the ML. The ML expectancy, an analytical method for determining the intermediate, is a very swift and expressway based on the principles of the Markovian chain in estimating the intermediate asset life. In achieving an ML expectancy, the transition of the asset for the failed and non-failed states are populated. The percentage of probability transition belonging to the same state can be generated. The deterioration probability can be assumed to the same state probability subtracted from 1. The ML expectancy as discussed by Thompson et al., (2012) is computed using Equation 6.13, where $\{P_{JJ}\}$ is the same state probability.

$$MLE = \frac{Log\ (0.5)}{Log\ (P_{jj})} \tag{6.13}$$

The ML deterioration could be gotten following the steps below to estimate the life expectancy using the ideas behind the Markov Chain as illustrated by Thompson et al., (2012) in the flow of the 6-steps listed below:

i. Starting from a previous and current inspection, collapse the states into failed and not failed.

ii. Group inspection data into pairs, using data with a yearly interval.

iii. Remove pairs that show signs of preservation leaving only pairs without maintenance.

iv. Obtained same state probability by dividing the non-failed state of past (Previous year) by the non-failed state of the present (Current year) from the calibrated data

v. The calibrated inspection data of the assets former condition state is utilised. The states are collapse into two states, a failed and not failed conditions.

vi. The ML expectancy design is computed based on 50% ~ 0.5 as expressed in Equation 6.13 with the indulgence that $\{P_{JJ}\}$ being the Not failed state is the same state probability.

The ML process is concluded with the assumption that the 50% ~ 0.5 threshold of the asset at its worst condition after the Markov model simulation is the ML of the system. The knowledge could be very beneficiary to systems where inspections have not been carried out in a yearly period by simply multiplying the ML by the inspection gap to express the life expectancy in term of years

6.4 CASE STUDY – CARRIAGEWAY SCANNER SURVEY

The first step in developing the Markovian model involved gathering two set of inspections data for carriageway assets between inspection periods, the previous state ($S_{PY} = i$) and current state ($S_{CY} = j$). The inspection data are grouped into pairs, each pair showing the change in defect condition of the asset. The pairs were uniform in length, and the inspection time interval was one year. Deterioration due to poor ride quality, rut depth, cracking and texture of the carriageway are extracted from the SCANNER survey. A total of 1720m of principal road carriageway length was collected with carriageway left (CL1) been 860m and carriageway right (CR1) 860m.

The deterioration model proposed intends to describe changes in condition if no maintenance action is taken to improve the state of the carriageway within the inspection period. For that reason, it is essential to take out data pairs that had a corrective action between the two conditions surveys conducted from the total data set. To detect possible repair activity and remove such pairs, the data was calibrated using Equation 6.14 indicating improvement condition as presented (Ford et al., 2012). Sections with positive improvement condition would be eliminated before the formation of the transition matrix. The equation is given as;

$$IC = Max_i \left(\sum_{j=1}^{i} S_{PY_j} - \sum_{j=1}^{i} S_{CY_j} - \right) \tag{6.14}$$

where IC is the improvement in condition for the inspection pair; i and j are condition states defined for the asset that was inspected (assuming that $j = 1$ is the best possible condition state);

$Maxi$ indicates maximisation over all possible condition states of the asset; S_{CYJ} is the fraction of the asset in condition state j in the second inspection (Current Year) of the pair; and S_{PYJ} is the fraction of the asset in condition state k in the first inspection (Previous Year) of the pair.

If one or more of the condition states show an increase in the fraction at its level or better, then IC is positive and indicate either that an error occurred in the inspection process or a preservation activity took place. In the absence of reliable maintenance records, the forecaster will often need to assume that all positive IC values indicate repair activity and will remove all such pairs from the data set conducted in the calibration of the UKPMS SCANNER survey data set from the SCANNER survey dataset for 2013 and 2014 inspection year as presented in Table 6.3.

Table 6-3 Improvement Condition from Calibrated UKPMS SCANNER Inspections

N	**Defect Types**	**Carriageway Section**	**Condition Survey Sample Length (m/section)** $S_{PY_J} - S_{CY_J}$	**Generated Calibrated Length (m/section)**
1	Ride quality (LV3)	CL1	860/43	520 / 26
		CR1	860/43	580 /29
2	Ride quality (LV10)	CL1	860/43	500 /25
		CR1	860/43	580 /29
3	Rut depth (LLRD)	CL1	860/43	400 /20
		CR1	860/43	320 /16
4	Rut depth (LRRD)	CL1	860/43	860 /43
		CR1	860/43	860 /43
5	Cracking(LTRC)	CL1	860/43	260 /13
		CR1	860/43	600 /30
6	Texture (LLTX)	CL1	860/43	860 /43
		CRI	860/43	820 /41
			10320/516	7160/358

6.4.1 Development of Current State (CS)

Percentage transformation is used to derive the CS distribution from the inspection survey data. For the current condition row vector, inspection data of carriageway defect are graded by a five-point RCI threshold. Inspection and repair actions are conducted to monitor the structural safety and maintain the performance over certain thresholds. However, these regimes must be tactically planned throughout the life cycle of an asset to ensure the optimum quality level, budget allocation and maximum service life without adverse effects on the structural system safety (Frangopol and Soliman, 2016). Although the original SCANNER survey rates its asset in a three-point colour coded rating as shown in Figure 6.2 in Section 6.2, it is perceived not to show a good enough spread and, thereby, does not provide adequate information on how critical its defects have affected the structure. The five-band scale developed thresholds are tabulated in Table 6.4 is introduced.

Table 6-4 Developed Five-Point RCI using SCANNER RCI Threshold

UKPMS Defect Characterisation	**SCANNER RCI Threshold**		**Designed RCI Threshold for Condition Bands**				
Defects Code	**Lower**	**Higher**	**VG**	**G**	**F**	**P**	**VP**
Ride Quality (mm^2) (LV3)	< 4	> 10	0 To ≤ 2	> 2 To ≤4	> 4 To ≤ 10	>10 To ≤12	> 12
Ride Quality (mm^2) (LV10)	< 21	> 56	0 To ≤ 10.5	>10 To ≤ 21	> 21 To ≤ 56	> 56 To ≤ 66.5	> 66.5
Rut Depth Nearside (mm) (LRRD)	< 10	> 20	0 To ≤ 5	> 5 To ≤ 10	> 10 To < 20	> 20 To ≤ 25	> 25
Rut depth Offside (mm) (LRRD)	< 10	> 20	0 To ≤ 5	>5 To ≤ 10	> 10 To ≤ 20	> 20 To ≤ 25	> 25
Cracking intensity (%) (LTRC)	< 0.15	> 2	0 To ≤ 0.075	> 0.075 To ≤ 0.15	> 0.15 To ≤ 2	> 2 To ≤ 2.075	> 2.075
Average Texture Depth(mm) (LLTX)	> 0.6	< 0.3	≥ 0.75	0.75 To ≥ 6	< 0.6 To ≥ 0.3	< 0.3 To ≥ 0.15	≤ 0.15

Improved: (Transport Research Laboratory, 2011)

The five-band scale redefines the initial RCI threshold and ensures that the lower and higher threshold defect ratings are maintained. The redefined band scale does not give a size contrary to established defect index created as offered by Transport Research Laboratory (2011) but provides an internal extension to give shorter spread carrying more bands. The threshold redefining makes it more appreciable to discern when the condition of the asset is still at a Very Good (VG) condition or VP condition. The ratio of each condition band for all defect is summed up together to form a whole condition band to the various defect. The percentage of each condition band is achievable by dividing the summation of each condition band by the total sample size. The row vector is calculated by aligning the defects measured using Current State (S_{CY}) inspection data. The progression is done by the measurement attributed to each condition state of the recommended five-point rating system using Equation 6.2 and the generated results illustrated in Table 6.5 are computed by means of Equation 6.15.

$$\{S_{CY}\} = \frac{S_{CY}\ \ B_n}{S_{CY}\ \ B_T} \tag{6.15}$$

This ratio provides the information for the quantity that will fall into the condition bands, and it provides a percentage formulation conversion with the consideration of total measurement. The quantity for each band is established from the total proportion of original asset quantification since the ratio of each condition band is known. The information about each condition band for each defect category is identified and recorded. The condition band information is very vital in the simulation and population of the future life of the assets once an appropriate transition probability matrix is developed or supplied. The percentage distribution of results generated represents CS, also known as the current status row vector. The state transition represented as a row vector of the asset band distribution is shown in Equation 6.16. The quantification indicates the expression of the CS condition in Figure 6.3 with (VG) 0.8566,(G) 0.1337, (F) 0.0097, (P) 0 and (VP) 0. The current situation is required for the Markovian chain simulation, expressing the various quantity of the individual condition band of the asset.

$$\{S_{CY}\} = \begin{bmatrix} VG & G & F & P & VP \\ 0.8566 & 0.1337 & 0.0097 & 0 & 0 \end{bmatrix} \tag{6.16}$$

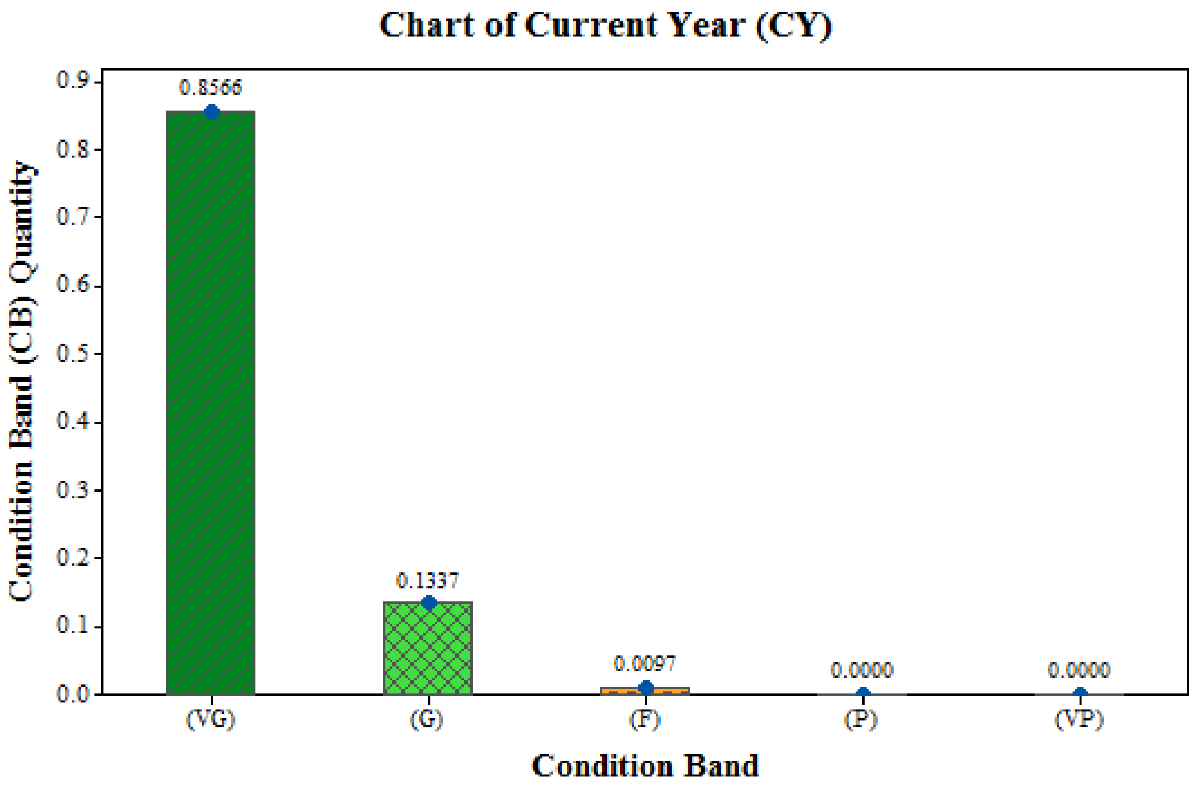

Figure 6-3 Current State condition (Year 2014) developed from UK SCANNER Data

6.4.2 Development of Linear Transition Probability (LTP)

For developing the transition probability matrix, only the calibrated samples having no maintenance support are utilised. The creation of the transition probability matrix consists of 358 portions (7160 m) of the SCANNER survey sample which totals has 516 portions (10320m) as portrayed in Table 6.3. Using the calibrated generated length in Table 6.3 and applying the five-point RCI threshold developed in Table 6.4, the calibrated length is distributed into various condition bands for the calibrated portions as shown in Table 6.5. The deterioration transition from the Previous Year (PY) to the Current Year (CY) within a one year period $P\ (PY \rightarrow CY)\ b_n$ in Equation 6.17 is used to estimate the ratio of the various condition band portions.

$$P_{(PY-CY)^{b_n}} = \frac{S_{b_{t-1}}^{Calibrated} - S_{b_t}^{Calibrated}}{S_{TotalPortion}} \tag{6.17}$$

where $S_{b_{t-1}}^{Calibrated}$ is the previous portion, $S_{b_t}^{Calibrated}$ is the current portion and $S_{TotalPortion}$ is the portion calibrated from the SCANNER survey sample that would remain or change band in their future year and result presented in Table 6.5.

Table 6-5 Calibration of Condition State Transition

Calibrated Portion	**VG → VG**	**VG → G**	**VG → F**	**VG → P**	**VG → VP**	**G → G**	**G → F**	**G → P**	**G → VP**	**F → F**	**F → P**	**F → VP**	**P → P**	**P → VP**	**VP → VP**
26	23	1	0	0	0	2	0	0	0	0	0	0	0	0	0
29	28	0	0	0	0	1	0	0	0	0	0	0	0	0	0
25	18	1	0	0	0	4	0	0	0	2	0	0	0	0	0
29	28	1	0	0	0	0	0	0	0	0	0	0	0	0	0
20	19	1	0	0	0	0	0	0	0	0	0	0	0	0	0
16	16	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	5	37	0	0	0	1	0	0	0	0	0	0	0	0	0
43	0	32	9	0	0	2	0	0	0	0	0	0	0	0	0
13	13	0	0	0	0	0	0	0	0	0	0	0	0	0	0
30	30	0	0	0	0	0	0	0	0	0	0	0	0	0	0
43	39	4	0	0	0	0	0	0	0	0	0	0	0	0	0
41	41	0	0	0	0	0	0	0	0	0	0	0	0	0	0
358	260	77	9	0	0	10	0	0	0	2	0	0	0	0	0

The deterioration transition from the PY to the CY of the calibrated sample is populated to develop an LTP to project the Future Years (FYs) condition. The use of linear transition amongst other methods is in its efficiency in the determination of the transition probabilities between two condition states at their earliest stage. The populated conditions as presented in Table 6.5 portrays the asset transition from PY to CY from the calibrated data generated from the sample inspection. The various condition bands are calculated by making a summation of one in the formation of the transition matrix from PY to CY for the continuous individual groups in simulating the FYs. The calculation below populates the ratio of the assets that will remain within each condition band after a one year's transition been developed from the decline from PY to CY in the calibrated survey result.

P_{IJ} (VG) = 260/358 = 0.726

P_{IJ} (G) = 77/358+10/358 = 0.215+0.0279 = 0.2429

P_{IJ} (F) = 9/358+2/358 = 0.0251+0.006 = 0.031

P_{IJ} (P) = 0/358 = 0

P_{IJ} (VP) = 0/358 = 0

To utilise the deterioration transition between inspection years, a linear transition is drawn up by replicating the result in a matrix form linearly for all condition bands as shown in Table 6.6.

Table 6-6 Linear Transition Probability Matrix

Transition Probability Between PY And CY					
	VG	**G**	**F**	**P**	**VP**
VG	0.726	0.243	0.031	0	0
G	0	0.726	0.243	0.031	0
F	0	0	0.726	0.243	0.031
P	0	0	0	0.726	0.274
VP	0	0	0	0	1

The LTP matrix in Table 6.6 lists the proportions of assets that would remain in a starting condition or move to a worse condition band after a deterioration cycle (over one year). After one deterioration cycle, the condition band as illustrated is an alternative expression in Equation 6.18 explains the transitioning probability matrix between the status bands.

- 72.6% in (VG) band, 24.3% in (G) band, 3.1% to (F) band the (P) and (VP) band has 0%;
- 0% in (VG) band, 72.6% in (G) band, 24.3% in (F) band, 3.1% to (P) and (VP) band has 0%;
- 0% in (VG) and (G) bands, 72.6% in (F) band, 24.3% in (P) band and band (VP) is 3.1%;
- 0% in (VG), (G) and (F) bands, 72.6% in (P) band and band (VP) is 27.6% (1- 72.6%);
- 0% in (VG), (G), (F) and (P) bands, 100 % in (P) band representing a completely failed state.

$$P = \begin{bmatrix} 0.726 & 0.243 & 0.031 & 0 & 0 \\ 0 & 0.726 & 0.243 & 0.031 & 0 \\ 0 & 0 & 0.726 & 0.234 & 0 \\ 0 & 0 & 0 & 0.726 & 0.274 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix} \qquad (6.18)$$

6.4.3 Development of Median Life (ML)

The ML is calculated based on inspection data calibrated and compared with a median of the VP condition state as calculated from LTP. Using the procedure adapted from Markov Chain model life expectancy (Ford et al., 2012) discussed in Section 6.3 of the report, the inspection data was categorised into failed and non-failed sets as represented in Table 6.7. The percentage transition for the failed and non-failed state is generated and grouped into pairs as shown in Table 6.7. The results provide the information on inspection defects in PY and CY. The % ratio of asset condition obtained from %∑ of the calibrated section and presented in Table 6.8. The transition probability in Table 6.9 is obtained by dividing the CY (Not Failed- 93.85) by PY (Not Failed- 98.96) in achieving the overall not failed state also known as the same state transition probability.

Table 6-7 Percentage Formulation of Failed and Not Failed Calibrated Section

	Previous Year (PY) %		**Current Year (CY)%**	
	Not Failed	**Failed**	**Not Failed**	**Failed**
LV3-CL1	98.08	1.92	97.12	2.88
LV3-CR1	99.14	0.86	99.14	0.86
LV10-CL1	92.00	8.00	88.00	12.00
LV10-CR1	100.00	0.00	99.14	0.86
LLRD-CL1	100.00	0.00	97.50	2.50
LLRD-CR1	100.00	0.00	100.00	0.00
LRRD-CL1	99.42	0.58	77.91	22.09
LRRD-CR1	98.84	1.16	69.77	30.23
LTRC-CL1	100.00	0.00	100.00	0.00
LTRC-CR1	100.00	0.00	100.00	0.00
LLTX-CL1	100.00	0.00	97.67	2.33
LLTX-CR1	100.00	0.00	100.00	0.00
%∑	1187.48	12.52	1126.25	73.75

Table 6-8 Average Asset Condition Before and After Inspections

	Previous Year (PY)		**Current Year (CY)**	
	Not Failed	**Failed**	**Not Failed**	**Failed**
%∑	1187.48	12.52	1126.25	73.75
% Ratio	98.96	1.04	93.85	6.15

Table 6-9 Probability Transition

Probability Transition		
	Not Failed	**Failed**
Not Failed	0.9484	1-0.9484

An asset starting at any condition state will deteriorate when continuously iterated by the transition probability matrix until it reaches a 0% level where further iteration is ineffective. The ML expectancy, which aligns with the principles of the Markov Chain, is a very swift and expressway. The transition from PY to CY of the asset for the failed and non-failed state is populated. The asset life is simulated until all the asset has failed. The period when a fraction of the failed state reaches 50% can be assumed to be the median asset life. The simulated future year's deterioration can give an estimate of the ML by merely flagging the state at which the failed state (VP) finally reaches 50%. In Succeeding the Equation 6.13, analytically, the ML expectancy is computed in as follows where (Pjj) is the same state transition probability obtained in Table 6.9.

$$ML\ expectancy = \frac{Log\ (0.5)}{Log\ (P_{jj})} = \frac{Log\ (0.5)}{Log\ (0.9484)} = 13.09th\ year \qquad (6.19)$$

6.4.4 Markovian Chain Simulated Prediction

In the projecting the first future year (FY1) from the analysis, the condition state is obtainable in a one-step transition process. The one-step simulates the CS row vector with the LTP formulated to generate the expected condition band outcome for the FY1. The FY1 transition simulation in Equation 6.20 is populated using the procedure in Equation 6.11 in Section 6.3. It includes the estimation of the CS (CY) in Equation 6.16 in Section 6.4.1.and LTP P (LTP) in Equation 6.18 from Section 6.4.2.

$$S_{(FYI)} = S_{(CY)}\ X\ \ P_{(LTP)} \tag{6.20}$$

The calculated future state S $_{(FY1),}$ being the exponentiation of the CS starting vector $_{(CY)}$ and the LTP $P_{(LTP)}$, both formulated from UKPMS SCANNER survey inspection data set is computed as presented in Equation 6.21.

$$\{S_{FY1}\} = \begin{bmatrix} VG & G & F & P & VP \\ 0.6219 & 0.3052 & 0.0661 & 0.0065 & 0.003 \end{bmatrix} \tag{6.21}$$

The state vector S (FY1) above shows how the proportions of assets have changed condition bands from S (CY) to S (FY1). It portrays the current quantity of bandspread of the condition bands after the first year where no maintenance activity is conducted. Comparison of carriageways condition bands for the S (CY) and S (FY1) is illustrated in Figure 6.4. While 0.8566 of the carriageway condition is VG at S (CY), only 0.6219 remained in VG condition band at S (FY1). While the quantity of carriageway in the VG category decreased, the portion of (G) increases from 0.1337 to 0.3052, (F) increases from 0.0097 to 0.0661, (P) and (VP) increase from 0% to 0.0065 and 0.0003 respectively.

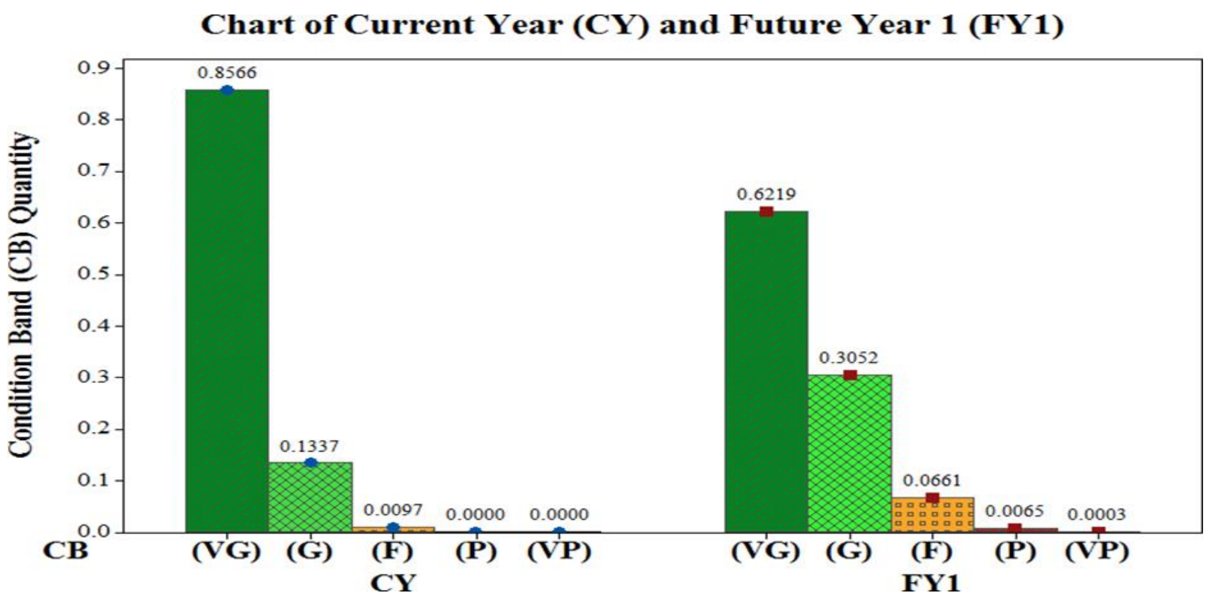

Figure 6-4 Predicted Future Deterioration One-Step Transition

Figure 6-4: Predicted Future Deterioration One-Step Transition

The future condition distribution at any time t can be populated (Wightman, Costello and Owen, 2011; Mc Dulling, 2006). The Markov discrete probability model can predict more than one performance level using a constant transition probability matrix. The nth transition probability is populated using matrix computation of Equation 6.22 derived from nth transition probability in Equation 6.12.

$$S_{(FYn)} = S_{(CY)}\, X\;\; P^{n}{}_{(LTP)} \tag{6.22}$$

The nth transition probability is populated using matrix computation. The CS row vector and the LTP matrix is initiated to form the iteration for 20 years. The simulated result is populated in line with the HMEP pairwise linear fashion from deterioration predictions in Table 6.10 for 20 years. The profile also includes a future projection for the degradation of the road for 20 years. The deterioration profile illustrating the predicted deterioration trend is shown in Figure 6.5.

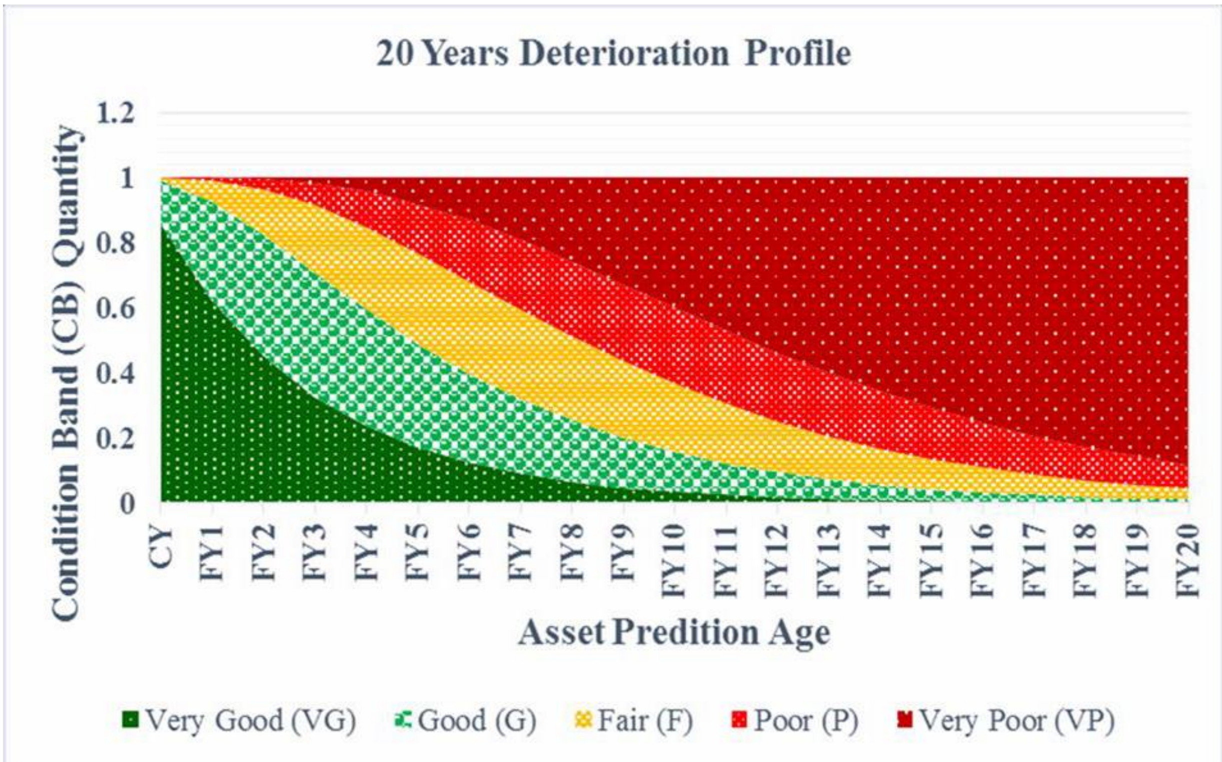

Figure 6-5 Deterioration Profile Using LTP Matrix

Table 6-10 Deterioration Predictions

Iteration	**Transition Iteration**	**Future Condition**	**Condition Bands**				
N	**Years**	**Years**	**VG**	**G**	**F**	**P**	**VP**
1	0	Starting	0.8566	0.1337	0.0097	0	0
2	1	FY-01	0.6219	0.3052	0.0661	0.0065	0.0003
3	2	FY-02	0.4515	0.3727	0.1414	0.0302	0.0045
4	3	FY-03	0.3278	0.3803	0.2072	0.0679	0.0172
5	4	FY-04	0.2380	0.3557	0.2530	0.1114	0.0422
6	5	FY-05	0.1728	0.3161	0.2775	0.1534	0.0806
7	6	FY-06	0.1254	0.2715	0.2837	0.1886	0.1312
8	7	FY-07	0.0911	0.2276	0.2758	0.2143	0.1917
9	8	FY-08	0.0661	0.1873	0.2583	0.2296	0.2590
10	9	FY-09	0.0480	0.1521	0.2351	0.2353	0.3299
11	**10**	**FY-10**	**0.0348**	**0.1221**	**0.2091**	**0.2327**	**0.4017**
12	**11**	**FY-11**	**0.0253**	**0.0971**	**0.1826**	**0.2235**	**0.4719**
13	**12**	**FY-12**	**0.0184**	**0.0766**	**0.1569**	**0.2097**	**0.5388**
14	**13**	**FY-13**	**0.0133**	**0.0601**	**0.1331**	**0.1927**	**0.6011**
15	14	FY-14	0.0097	0.0469	0.1117	0.1741	0.6581
16	15	FY-15	0.0070	0.0364	0.0928	0.1550	0.7092
17	16	FY-16	0.0051	0.0281	0.0764	0.1362	0.7546
18	17	FY-17	0.0037	0.0217	0.0625	0.1183	0.7943
19	18	FY-18	0.0027	0.0166	0.0507	0.1018	0.8286
20	19	FY-19	0.0020	0.0127	0.0409	0.0867	0.8581
21	20	FY-20	0.0014	0.0097	0.0329	0.0733	0.8831

The simulated results could be utilised for various purposes such as maintenance planning and cost projection as the spreads show the asset conditions state on a yearly basis for 20 years. The result depicts the change that occurs in different condition states of the assets. As initiated from Equation 6.20 also expressed in Table 11, the assets had a percentage of 0.8566~85.66% in VG in CY also known as CS deteriorates to 0.6219~62.19% in FY1 in Figure 6.4. The nth resultants from Equation 6.20 for VG projects a reduction to 0.4515~45.15% for FY2, 0.3278~32.78% for FY3, 0.2380~23.80% for FY4 and barely 0.0348~3.48% remain at a VG state in FY10 as indicated in Table 6.10. The predicted condition state could assist asset managers to understand the deteriorations of their asset and help to identify when its best to carry out maintenance actions. Every asset owners look forward to ensuring that their asset is above the fair level because it will enable them to avoid more reactive maintenance and provide more preventive and CBM. The Markov Chain model still happens to be one of the most appropriate tools for predicting the future condition of the physical asset. The deterioration profile as shown in Figure 6.6 is illustrating the 20 years spread between the various condition states. The deterioration levels after every other five years (i.e. 5years, 10 years, 15 years and 20 years) are presented in Figure 6.6.

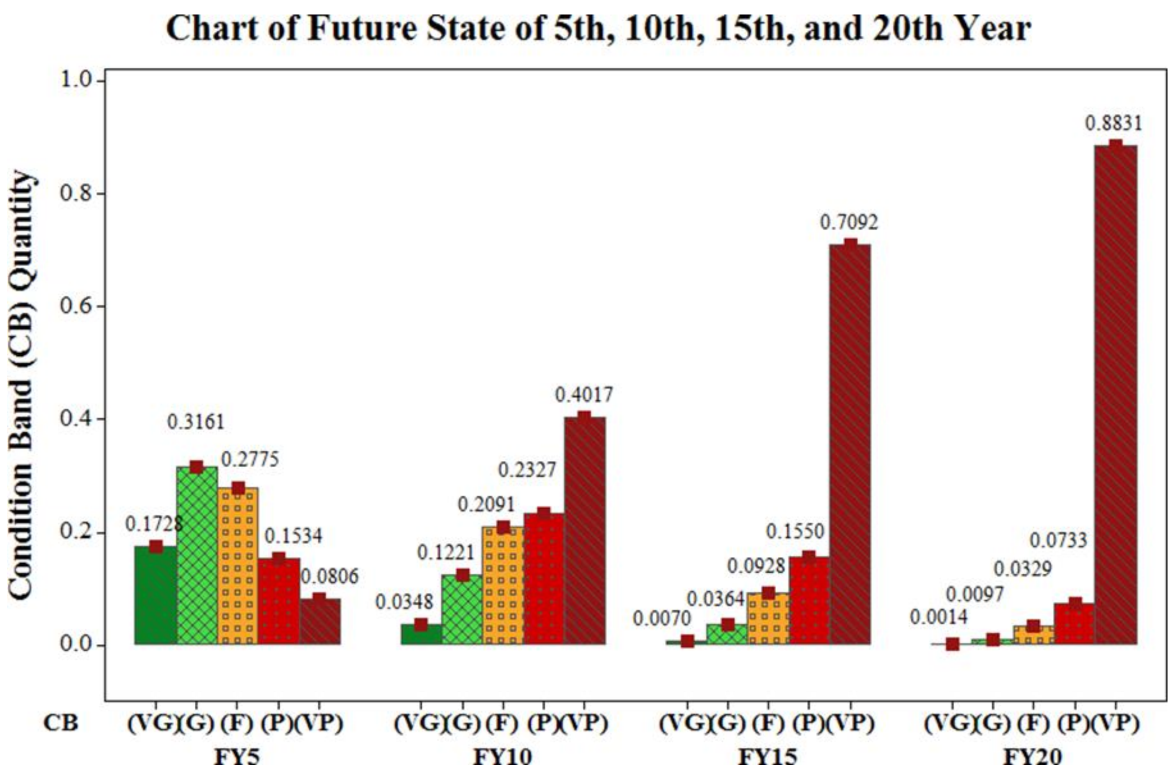

Figure 6-6 Projected Future State Using Linear Transition Probability Matrix

6.4.5 Parametric Analysis

The statistical mean and standard deviation computed are presented in Table 6.11 for the various condition band simulated projections. The Cumulative Probability Distribution (CPD) indicating the precise FYs of the VP band for the twenty-one iterations portrays the precise deterioration trend the carriageway is likely to follow as identified in Table 6.12.

Table 6-11 Statistical Representation of Condition Bands Simulated Predictions

Variables	VG	G	F	P	VP
Iteration	21	21	21	21	**21**
Mean	0.1487	0.1539	0.1504	0.1401	**0.4074**
StDev	0.2332	0.1317	0.09159	0.07566	**0.3261**

The empirical CDF is introduced due to its ability to reveal the normal distribution to achieve the perfect fit for the predictions of VP condition. This introduction helps estimate the percentiles for the FYs deterioration of the VP band predictions to capture the future asset life decline. The three MLs (Simulated LTP, Statistical and Analytical) of the VP condition band FYs as presented in Table 6.13. The 20 years' time series for the decline prediction plot portrays the empirical CDF location of all the resolved ML as shown in Figure 6.7.

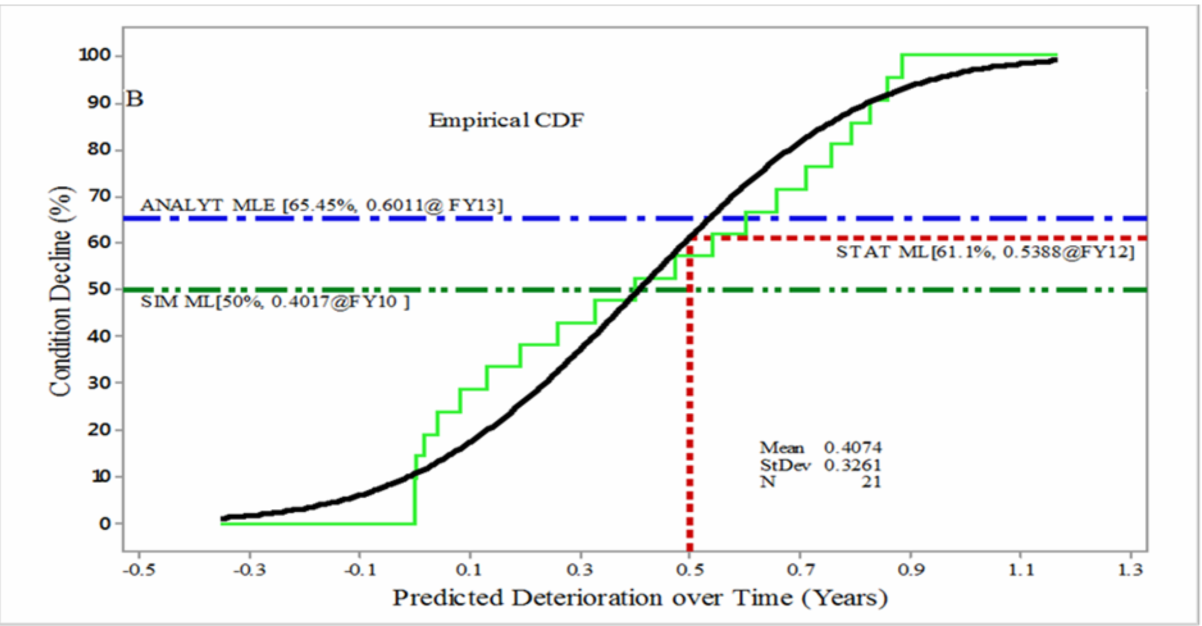

Figure 6-7 MLs Comparisons via 20years Deterioration prediction

Table 6-12 Cumulative Distribution Probability of VP

Transition Iteration	**FYs**	**VP (X)**	**CPD (Y)**
1	0	0	0.04762
2	FY-01	0.0003	0.09524
3	FY-02	0.0045	0.14286
4	FY-03	0.0172	0.19048
5	FY-04	0.0422	0.23810
6	FY-05	0.0806	0.28571
7	FY-06	0.1312	0.33333
8	FY-07	0.1917	0.38095
9	FY-08	0.2590	0.42857
10	FY-09	0.3299	0.47619
11	**FY-10**	**0.4017**	**0.52381**
12	FY-11	0.4719	0.57143
13	**FY-12**	**0.5388**	**0.61905**
14	**FY-13**	**0.6011**	**0.66667**
15	FY-14	0.6581	0.71429
16	FY-15	0.7092	0.76190
17	FY-16	0.7546	0.80952
18	FY-17	0.7943	0.85714
19	FY-18	0.8286	0.90476
20	FY-19	0.8581	0.95238
21	FY-20	0.8831	1

The simulated result portrays that the LTP ML [0.5 Probability Distribution (PD) at the deterioration level of 40.17% will occur in the FY10]. The statistical ML [53.88% deterioration level of 0.611 PD occurring at FY12] and finally the expected ML using analytical method [FY13.09 at a PD of 0.667 has a 60.11% condition life left] as tabulated in Table 6.13. Although all three MLs falls between FY10 – FY13, the ML expectancy happens to exhibit the most extended expression for the Median life at VP of 60.11% deterioration profile.

An empirical CDF can be more effective in benchmarking against the result of the ML expectancy calculated using the fast-analytical method in Equation 6.19 and the assumptions simulated ML deterioration prediction of VP condition in row 13 column 7representing the 12th year in Table 6.12. It was computed that the statistical ML of 52.38% is the 10th year which falls between FY 09 (47.19%) and FY11 (57.14%) as shown in the CPD column in Table 6.12.

Table 6-13 Median Life's (MLs) Correlation of VP

Transition Iteration/Row	**Future Years**	**VP %**	**Probability Distribution %**	**Median Life**
11	FY-10	40.17	52.38	Statistical
13	FY-12	53.88	61.95	Simulated LTP
14	FY-13.09	60.11	66.66	Analytical MLE

6.5 SUMMARY

Automated condition surveys are currently introduced for condition assessment of highway infrastructure worldwide. Accurate predictions of the current state [CY], ML and future states [FY] of road and highway infrastructures are crucial for developing appropriate inspection and maintenance regimes for newly created or existing highway infrastructure. The proposed methods are applied and evaluated using condition improvement between the two successive inspections from the SCANNER survey of the United Kingdom Pavement Management System. The proposed LTP matrix model utilised better insight than the generic or decoupling linear approach used in estimating transition probabilities formulated in the past. The simulated LTP predicted conditions was portrayed in a deterioration profile and a pairwise correlation. An asset starting at any condition state would deteriorate when continuously iterated by the transition probability matrix till it reaches a 0% level where further iteration is ineffective and the period when a fraction of the failed state reaches 50%, can be assumed to be the median asset life. The development of the state condition from the automated SCANNER machine produced results which convey that the ratio of individual condition band for an asset when summed up together equals to 1 as expressed in the current state condition in Figure 6.3. The percentage of each condition band is achievable by dividing the summation of each condition band by the total sample size. The MLs are computed statistically with a CDF plot. The chapter concludes that an ML expectancy is ideal for projecting half asset life, and the linear transition matrix approach presents a feasible approach for new maintenance regime pending when more certain deterioration data types become available.

CHAPTER 7: COST MODELLING OF TREATMENT TRANSITION

7.1 INTRODUCTION

The chapter aims to support decision making to determine an optimal intervention type, as well as a selection of the best alternatives via variable investigation (performance condition and treatment renewal) that affect an optimal steady state of the road network. A study in the estimation of infrastructure transition probabilities from condition rating data has proven that information on current, and future infrastructure conditions are essential for maintenance and rehabilitation decision making (Madanat et al., 1995). Due to a paradigm shift in core maintenance, maintenance performance measurement has gained considerable attention from the practitioner and researchers in recent years (Parida and Kumar, 2006). Performance measurement forms the basis for considering where treatments and most pertinent in maintenance considerations. Performance measurements along with treatment transition are used to develop cost models, because of the high probability that performance conditions and treatment renewals actions portray the treatable asset constitutes for the forthcoming period. These attributes have gained importance because asset owners and managers are interested in knowing the relationship between the CS of their asset and the output of the maintenance process.

Recent research findings portray that organisations been managed using integrated performance measurements systems out-performs organisations where performance measures are not in place as well as having superior stock prices than those (Parida et al., 2015). The likelihood of optimal performance is the function of the previous state (before treatment), the treatment type and treatment cost in obtaining its future state (after treatment). Treatment strategies that could bring the asset back to the start of initial condition or better than its CS are often-wished-for when considering maintenance plans for the treatable asset. Asset owners and providers are under immense pressure to adequately maintain and improve the level of service and performance despite a shortage of funding. Their success is determined by their ability to reduce the level of expenditure without taking on additional risk or adversely affecting the performance of the asset over the asset lifecycle. Therefore cost estimates are vital as an alternative strategy to benchmark the dwelling funding for highway asset maintenance in consideration of capital investment and maintenance plans.

Maintenance of deteriorating carriageway system can be a significant challenge since their process of degradation portrays unpredictable random failures occurring from traffic loads on the carriageway and effect of weather. These uncertainties often lead to typical questions when maintenance is deliberated such as:

- What are the best maintenance alternatives?
- The frequency of maintenance and
- What level of deterioration is acceptable before maintenance considering maintenance?

Optimisation is an act, process, or methodology of making something (such as a design, system, or decision) as fully perfect, functional, or effective as possible. As a result, most treatment intends to bring the asset to a renewed state known as the optimal level, Nevertheless, the maintenance action often leaves them at steady state or worse than before (Carnahan et al., 1987).

7.2 STRATEGIC ALGORITHM

Inspection ratings are often used in classifying asset conditions; these ratings are discrete ordinal measurements often representing a relative order obtained by discretising its continuous performance scale (Carnahan et al., 1987; Madanat et al., 1995). This chapter uses a five-point rating approach to illustrate performance conditions in proposing ten prospective treatment strategies for developing the analytical cost model. The five-point approach informs the level of degradation of the CS proportion of the system. The understanding of the performance condition is vital for useful application and grading of the asset deficiencies, which entails, identifying areas of the asset that is profoundly affected by defects that lead to higher risk of failure and requiring the significant cost to either restore or repair the assets.

Several integrated carriageway management systems have deployed the use of condition states for simplicity and practicability for effectiveness in integrating both carriageway deterioration rates and improvement rates resulting from maintenance and rehabilitation actions into a single entity for effective optimisation (Abaza et al., 2004). As the asset is ageing, they require an ever-increasing amount of investment for their upgrade and maintenance in sustaining the designed performance level. Aligning asset performance to condition bands enables the characterisation of the asset all through the various state of its long life and complex deterioration. The knowledge of the way the assets deteriorate over time is expressed by the changes in performance conditions which help reveal how the degradation would affect the maintenance and rehabilitation cost and the risk to the users.

7.2.1 Five-Point Performance Condition

The asset condition is classified using a five-point band namely 1 –Very Good (VG), 2-Good (G), 3-Fair (F), 4 Poor (P) and, 5-Very Good (VP) with the description of the status groups as defined and expressed in Table 7.1 (Riveros and Arredondo, 2014).

Table 7-1 Description of Condition Band Performance

Band	Performance Condition
Very Good (T_1)	Pavement is sound, functioning correctly, and having no deficiency. Its performance or reliability is as designed
Good (T_2)	Pavement member is beginning to show signs of deficiency. They are sound with no impact on performance or reliability
Fair (T_3)	Deficiency has advanced. Thou members still function as intended; unabated wear will lead to the next condition state
Poor (T_4)	Deficiency has advanced to the point that function may be impaired. The asset is not serving its proposed purpose, reliability and safety to road users
Very Poor (T_5)	Deficiency has advanced to the point that the member no longer serves its proposed function and safety to road users

These condition states represent the asset condition over time. The rating system used is most appropriate as supported by literature because it reduces the computational complexity of the maintenance decision making process (Abaza et al., 2004). Although ordinal pavement condition state classification used in the past utilised state representation 1,2,3,4,5,6,7 and 8 having a corresponding state classification (1 ~ Failed) and (8 ~ Excellent) (Carnahan et al., 1987; Madanat et al., 1995). The five-band condition utilised in this research constitutes the proportion of the asset performance state. This boundary is the assumptions that Chapter 7 will be based upon when discussing the structural health monitoring of the asset both from the performance condition and the treatment renewal analysis. The performance state summary describes the expression of the condition band based on the performance, reliability and safety of the state of the asset. The five-point performance condition band covers the asset at the optimal level VG as well as a state of severe deficiency VP. The five-point performance groups are implied as follows 1 –VG (T1), 2-Good (T2), 3-Fair (T3), 4 Poor (T4) and, 5-VP (T5).

7.2.2 Prospective Treatment Strategies

The most appropriate treatment approach is required to return an asset to its original state. The treatment methodology for a five-band performance condition application can be structured into ten prospective treatment stratagems. Treatment on asset brings the health to a level above its current situation or the desired level. Figure 7.1 reveals the ten potential treatment strategies derived from the assets five-point performance status view. The five-point performance condition represents T1: VG, T2: Good (G) T3: (Fair) F, T4: Poor (P) and T5: VP. The prospective treatment strategies denote 0, 1, 2… 10. The procedures which follow in transitions portrays T2-1 been the asset at a Good (G) state requiring maintenance to bring to a VG state (G →VG). The loop T5-10 represents the VP state requiring maximum repairs intervention to bring to a VG state (VP →VG) is the optimisation criteria as expressed in Figure 2 along with its other alternatives.

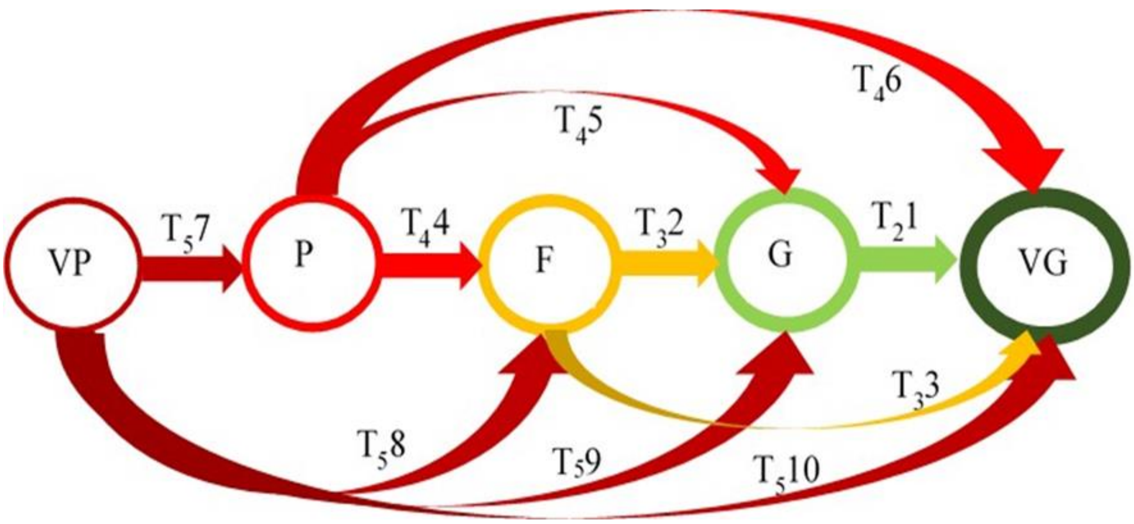

Figure 7-1 Treatment Intervention Strategies

7.2.3 Cost Modelling Application

The analysis introduced illustrates the use of cost modelling using carriageway records and performance condition results. The results are developed from SCANNER surveyed condition data obtained from a United Kingdom road survey presented in Chapter 6. The investigation conducted aims to demonstrate the use of cost modelling on roadway asset. The analysis considers treatment transitions alternatives for strategic cost optimisation. The pavement data employed in the analysis are from the TfL road network. A strategic model algorithm for cost modelling of roadway asset is developed and presented in Figure 7.2. The strategic model algorithm accesses the asset on a yearly cycle in determining the forthcoming category from the known CS condition bands. The algorithm displays the revolution when treatment intervention is introduced or not. The development of the performance condition, the treatment effect and the analytical cost optimisation are presented following sessions. The procedure as shown in the strategic model in Figure 7.2, displays the trail of the strategic model to enable assets owners to gain understanding on when best to carry out treatment for their asset. The performance condition requires variables from the current condition of the asset and the utilised performance transition in computing its future state. However, in the case of the treatment renewal the current condition bands, the area proposed for treatment and the treatment cost of the repair level desired. The definition of the strategic model variable in Figure 7.2 are discussed in Table 7.2 for ease of reference.

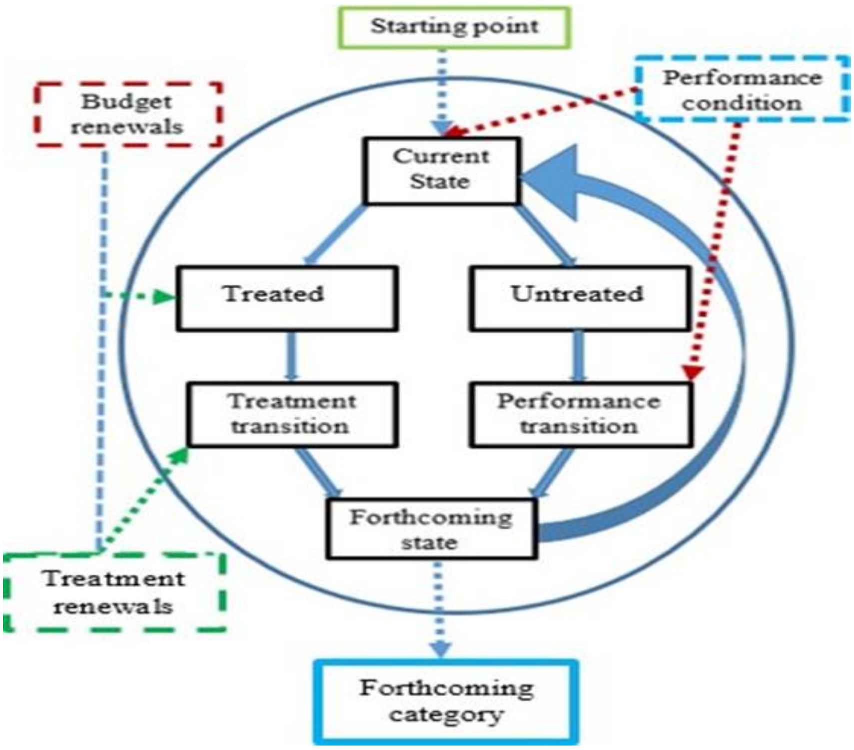

Figure 7-2 Strategic Model Algorithm

Table 7-2 Definition of Strategic Model Variable

N	Strategic Model Variable Definition
i	**Budget renewals:** The annual budgeted figure needed for each of the treatment types for various asset
ii	**Current state:** The state of which the asset represents before modelled for a forthcoming state
iii	**Condition band:** The categories of the asset condition being modelled ranging from VG to VP
iv.	**Forthcoming state:** The projected state from the CS with a view of the treated or untreated quantity
v.	**Performance condition:** The forthcoming condition of the CS having no treatment action on asset
vi.	**Performance transition:** The transition probability matrix in a deterioration context
vii.	**Treated quantity:** The portion of an asset that is undergoing treatment intervention during the modelling revolution
viii.	**Treatment renewals:** The forthcoming condition of the CS having treatment action
ix.	**Treatment transition:** The transition probability matrix in an improvement context
x.	**Untreated quantity:** No maintenance work conducted within the modelling period

7.3 PERFORMANCE CONDITION

The asset performance condition is classified using five-points band viz. 1 –VG, 2-Good, 3-Fair, 4-Poor and, 5-VP. The condition band is the starting point (CY) for subsequent planning for the network. The current situation performance status and performance transition initiated in Chapter 6 are introduced for the CS and performance change for populating the untreated forthcoming year.

7.3.1 Current State (CS)

The estimation for CS is imperative as it represents the definition of the asset condition used in describing the condition bands (Dean et al., 2012). The percentage distribution developed expressing the current situation composition in Chapter 6; Section 6.4.1 is presented in Table 7.3. The quantification indicates the inventory of the carriageway sample used for the analysis and the expression of the CS.

Table 7-3 Condition Band

Inventory (M)		**Derived Current State (%)**				
L	W	VG	G	F	P	VP
1720	7.8	85.66	13.37	0.97	0.00	0.00

7.3.2 Performance Transition

In the simulation of the untreated forthcoming condition states, transition probability from two consecutive inspection periods having no maintenance intervention is essential. (Ortiz-garcía, Costello and Snaith, 2006; Wellalage, Zhang and Dwight, 2014). Lifecycle planning toolkit is incorporating default carriageway deterioration models by HMEP futures several methods for developing transition matrices (Highway Maintenance Efficiency Programme, 2012b). The transition probability derived in Chapter 6, Section 6.4.2 which has linear characteristics is considered most appropriate for setting up any new treatment intervention regime and is used in the analysis for continuity and consistency. The linear transition being an undeviating transition matrix replicate its transition probability from a higher state to a lower state in their deterioration pattern as shown in Table 7.4. The row of the performance transition continuously sums up 100%.

Table 7-4 Performance Transition

Derived Performance Transition %						
Band	**VG**	**G**	**F**	**P**	**VP**	**(%)**
VG	72.6	24.3	3.1	0	0	100
G	-	72.6	24.3	3.1	0	
F	-	-	72.6	24.3	3.1	
P	-	-	-	72.6	27.4	
VP	-	-	-	-	100	

7.3.3 Forthcoming State (Untreated Quantity)

The effect of no treatment on an asset in a yearly cycle period naturally leads to an adverse change in the condition band of the asset for the future year. The forthcoming condition bands are derived from the multiplication of the CS and Performance Transition as presented in using Equation 7.1

$$\text{Forthcoming State (FS)} = \text{CS x PT} \qquad (7.1)$$

where FS is the forthcoming State, CS is the current state, and PT is the Performance Transition.

The FS, been the resultant of the CS condition band and the performance transition having no treatment intervention for a one-year cycle is expressed in Table 7.5 displaying how the % appropriation of its CS and performance transition is obtained. The future resultant state as computed for the untreated quantity is presented as shown in Table 7.6. The resultant condition shows signs of decreases as expected but a trend that is portraying continuous decline.

Table 7-5 Current State (CS) against Performance Transition (PT)

CS %			**PT %**				
Band	QTY		VG	G	F	P	VP
VG	85.66		72.6	24.3	3.1	0	0
G	13.37		0	72.6	24.3	3.1	0
F	0.97	**X**	0	0	72.6	24.3	3.1
P	0		0	0	0	72.6	27.4
VP	0		0	0	0	0	100

Table 7-6 A Forthcoming State for Untreated Quantity

Band	**Forthcoming State – One Transition (%)**				
QTY	VG	G	F	P	VP
100	62.19	30.52	6.61	0.65	0.03

The Forthcoming state when analysed with consideration of the current situation, portrays a deterioration decrease in the VG condition band (CS~85.66% declined to FS~62.19%). The other condition bands depict increased with G (CS~13.37% amplified to FS~30.52%), F (CS~0.97% improved to FS~62.19%) as well as P and VP. The increase in the FS as depicted in the bar chart in Figure 7.3 epitomising the change from the CS to its future state.

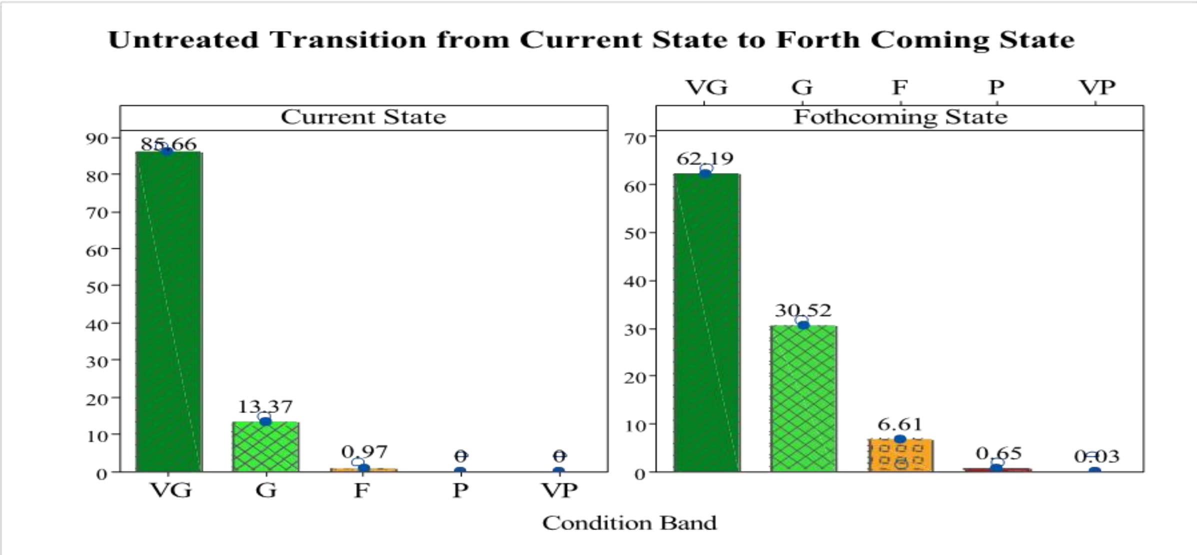

Figure 7-3 Condition Transition from Current to Forthcoming

7.4 TREATMENT RENEWALS

Treatment of carriageway can be classed into several treatment types (Dean et al., 2012). In the analysis, the assumption accommodates four treatment types, namely, surface dressing, moderate overlay, deep inlay, and reconstruction. The treatment effect and cost variable required for the expected performance condition after treatment intervention can be obtained using the following;

- Treatment unit cost,
- The treatment effect of expected FS,
- Area of CS for treatment.

7.4.1 Treatment Unit Cost

The various treatment types named; surface dressing, moderate overlay, deep inlay and reconstruction as classed in Table 7.7 defining their assumed unit cost.

Table 7-7 Effect of Treatment Types and Cost

Treatment Types	Cost £/M^2	Condition Band				
		VG	G	F	P	V P
Dressing	8.5	*	VG	G	F	P
Overlay	25	*	*	VG	G	F
Inlay	42	*	*	*	VG	G
Reconstruct	60	*	*	*	*	V G

7.4.2 Treatment Transition

Although it is not economical to carry out treatment yearly, planned treatment intervention always aims to bring the asset to a state as good as new. Table 7.8 describes the likely scenarios of treatment type %, recommended for the carriageway layer to improve its transition to an optimal level. For example, the asset in a (VP) condition requires a full reconstruction. Such treatment requires 100% wearing course, 100% binder course and 100% base course to transit the asset to a (VG) condition. However, in a situation when the asset is at a Poor (P) or Fair (F) state, it would require treatment repair level of 100% wearing course and 100% binder course, a 30% and 15% base course were necessary respectively.

Table 7-8 Treatment Types

Band	VG	G	F	P	V P
Repair Level	-	Surface Dressing	Moderate Overlay	Deep Inlay	Re construct
Wearing Course	-	100%	100%	100%	100%
Binder Course	-	15%	100%	100%	100%
Base Course	-	0%	15%	30%	100%

7.4.3 Forthcoming State (Treated Quantity)

The effect of treatment intervention on an asset often brings it to a state as good as new. Nevertheless, an asset at any current condition can undergo transition treatments to take them to an optimum state as portrayed in the ten steps scenarios in Table 7.9 from the treatment intervention strategy in Figure 7.1 from Section7.2.2.

Table 7-9 Description of Condition Band Performance

C-S	**Transition**	**Strateg ies**
T_1-0	VG →VG	No treatment –Routine Inspection
T_2-1	G →VG	Treat at Good ~ (T_2) and bring the asset to Very Good ~ (T_1)
T_3-2	F →G	Treat at Fair ~ (T_3) and bring the asset to Good ~ (T_2)
T_3-3	F →VG	Treat at Fair ~ (T_3) and bring the asset to Very Good ~ (T_1)
T_4-4	P→F	Treat at Poor ~ (T_4) and bring the asset to Fair ~ (T_3)
T_4-5	P→G	Treat at Poor ~ (T_4) and bring the asset to Good ~ (T_2)
T_4-6	P→VG	Treat at Poor ~ (T_4) and bring the asset to Very Good ~ (T_1)
T_5-7	VP →P	Treat at Very Poor ~ (T_5) and bring the asset to Poor ~ (T_4)
T_5-8	VP →F	Treat at Very Poor ~ (T_5) and bring the asset to Fair ~ (T_3)
T_5-9	VP →G	Treat at Very Poor ~ (T_5) and bring the asset to Good ~ (T_2)
T_5-10	VP →VG	Treat at Very Poor ~ (T_5) and bring the asset to Very Good ~ (T_1)

Asset at the various status band level can be repaired to reach the subsequent desired level treatment depending on the budget constraints. The states represented in Table 7.9, would be the resultant for a current situation condition when maintenance treatment is introduced within the yearly cycle using the treatment transition. The future state, when treated, is expected to bring the asset to a perfect state or as good as new. The anticipated status for a new asset typically consists 100% of the VG condition band and 0% for the other condition groups namely, Good (G) 0%, Fair (F) 0%, Poor (VP) 0% and VP 0% respectively as represented in

Equation 6.4 of Chapter 6. Nevertheless, the treatment transition when the CS developed is introduced, portrays an increase in the VG condition band and a decrease in the other categories as shown in Table 7.10. The VG condition is improved to 100% from 85.66%, while the other groups automatically decline to 0% as shown in Table 7.10.

Table 7-10 A Forthcoming State for Treated Quantity

Band	**Forthcoming State – Treated**				
	VG	**G**	**F**	**P**	**VP**
Current State (%)	85.66	13.37	0.97	0	0
Forthcoming State (%)	100	0	0	0	0
Five-Point Scale	1	2	3	4	5

7.5 ANALYTIC COST OPTIMISATION

The optimal treatment level using the most efficient cost estimate for treatment change from one condition band to another is obtainable from an expert illustration or maintenance records (Highway Maintenance Efficiency Programme, 2012a). The unit cost used for the analysis is an assumption as diverse treatment types do currently exist, at various prices and measurement depending on the application type. The elicited unit cost utilised is computed with consideration of the desired performance condition band. The treatment transition scenarios, optimal treatment level, and cost estimation combination express the forthcoming year repair cost analytically. It is the intent of every asset owner to desire a network operating at an optimal performance level of VG. Thus, the anticipated future treatment renewal is achievable by applying a treatment intervention that will bring the asset to a state as new. As shown, for the anticipated optimal level FS, the treatment strategies intervention portrays options for best decision making and implementation.

7.5.1 Analytic Cost Formulation

Every asset at a new state depicts the optimal performance, reliability, and safety. In retaining such a circumstance, it is intended for the asset owner to carry out the expensive method of actualising their expected performance level. Nonetheless, the use of an analytical cost optimisation gives the asset owner alternatives towards minimal cost scenarios to apply and achieve an optimal performance level. The five-point performance condition band rating/distribution in Table 7.9 helps give a guide for the easy understanding of the comparative range of each condition group status. Treatment intervention strategy for each scenario can be computed using the following variable as stipulated in Equation 7.2.

$$TI = C_b \text{ x } A_s \text{ x } T_c \qquad (7.2)$$

where C_b is the current condition band, As is the area of the sample and Tc is the cost of treatment.

The individual ranking of the condition band that the asset currently reside is VG~1, G~2, F~3, P~4 and VP~5. For example, if an asset at VP state requires an upgrade to VG, the treatment strategy of reconstruction is considered as expressed in scenario T510. Equation 7.2 is utilised to obtain the estimation analytically against other scenarios as presented in Table 7.11. The estimation is helpful in deriving the prospective strategies for the cost of maintenance of the forthcoming year. In using the analytically formulated approach, the best value is obtained and could be altered as desired, as it depends on the variables:

i. CS for treatment intervention,

ii. The expected performance level,

iii. The predicted forthcoming performance condition.

7.5.2 Prospective Cost Strategy

The cost of maintaining a carriageway depends on its condition or state. It is often expected that maintenance or rehabilitation funds be allocated to carriageway or areas of the carriageway that are in the worst state of exhibiting an accelerated rate of deterioration (Carnahan et al., 1987; Carnahan, 1988). When the construction project lags, the proposed construction in the programme designed, it is often anticipated that the project has cost more than expected. The cost deviation is usually not the random variation of the actual cost, but evidence of underestimation of the overall project cost collectively. Thus it is essential for the decision makers to consider the options that may require a higher initial investment but will yield lower cost and risk but higher performance over the life of the asset (Parlikad and Rengarajan, 2016).

The strategy developed for the five-point condition band relays the treatment consequence and cost variable in the perspective of ten prospective strategies proposed as presented in Table 7.11.

Table 7-11 Cost Variables via Prospective Maintenance Strategy

Transition	C		M2		£/M2	Total cost	Strategy
G→VG	2	x	(1720 x 7.8)	x	8.5	£228,072	$T_2$1
F →G	3	x	(1720 x 7.8)	x	8.5	£342,108	$T_3$2
F →VG	3	x	(1720 x 7.8)	x	25	£1,006,200	$T_3$3
P →F	4	x	(1720 x 7.8)	x	8.5	£456,144	$T_4$4
P →G	4	x	(1720 x 7.8)	x	25	£1,341,600	$T_4$5
P →VG	4	x	(1720 x 7.8)	x	42	£2,253,888	$T_4$6
VP →P	5	x	(1720 x 7.8)	x	8.5	£570,180	$T_5$7
VP →F	5	x	(1720 x 7.8)	x	25	£1,677,000	$T_5$8
VP →G	5	x	(1720 x 7.8)	x	42	£2,817,360	$T_5$9
VP →VG	5	x	(1720 x 7.8)	x	60	£4,024,800	$T_5$10

For case in point in the study, the treatment transition plans which brings the carriageway with condition band at VP to VG would cost £60 per m2 for reconstruction, costing £4,024,800 based on the area measured for maintenance. However, if a Good (G) or Fair (F) condition state level is desired from a current Poor (P) condition, the estimated Poor (P) → Good (G) cost is £1,341,600 at £25 per m2 for an overlay. In line with the same principle, the Poor (P) → Fair (F) cost £456,144 at £8.5 per m2 for moderate dressing. Most of the time the treatment intervention that would produce the best outcome happens to carry the highest maintenance cost, thus expensive to implement. Knowing the analytic value of all possibility gives alternatives to what repair level to undertake and the condition band level as well desired before conducting repairs. The ten potential plans describe the cost, and the treatment repair level in the similitude of an exploratory data analysis in Figure 7.4 about the price approach adopted. The strategic cost of the asset illustrates the condition transformation from a CS to the future state. The strategies portray the costs of change for an alternative. All asset condition fits into one of the ten strategies notwithstanding the current condition of the system, and the cost optimisation is enhanced for selected treatment policy.

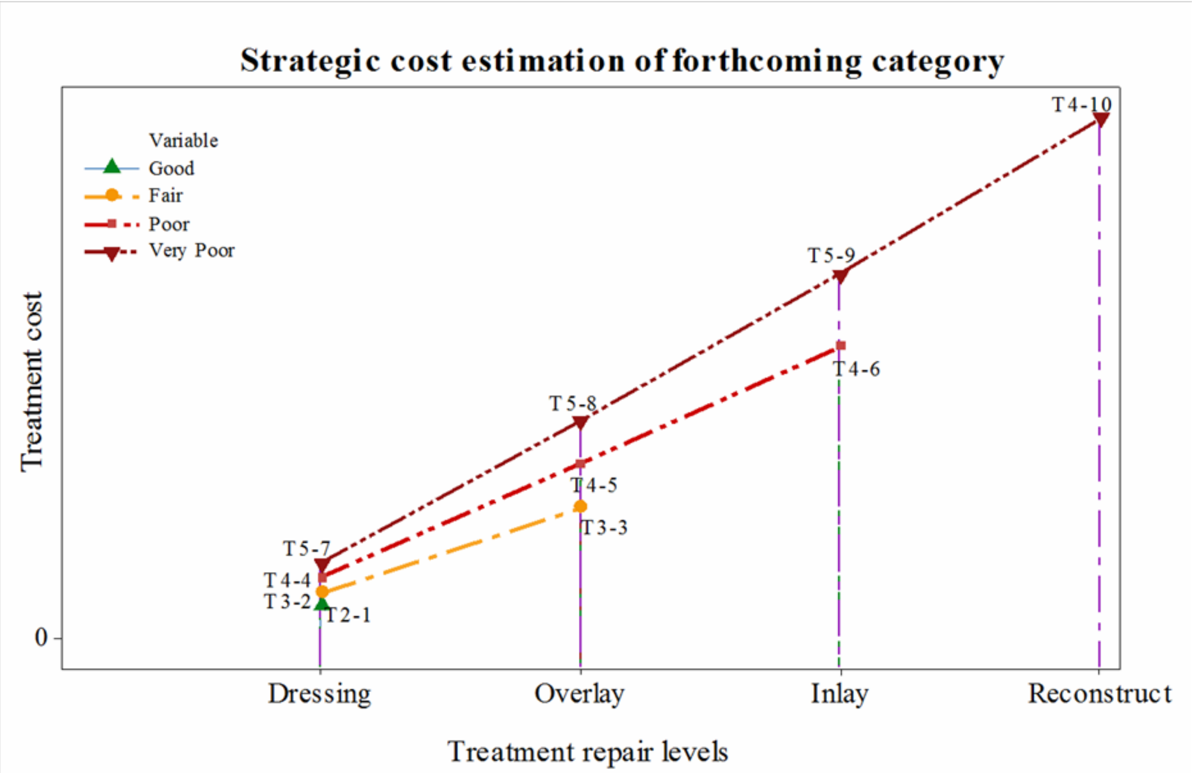

Figure 7-4 Strategic Cost Optimisation of Forthcoming States

The price margin that is both costs efficient and in line with budget renewal is taking into consideration. The use of cost optimisation will help define the boundary between minimising the cost of maintenance as well as increased mean time to transition intervention. Table 7.12 presents the relationship between the level of repair type and the strategic cost of the asset condition transformation for the FS. The strategies portray the costs of the transformation of all strategies aside from the condition of the system. For illustration, an asset manager wants to find the appropriate transition intervention that will maximise the yield from his annual or long- term budget. The budget is best controllable using the knowledge of the asset performance condition, budget capital renewal and treatment renewal. The forthcoming untreated and treated condition can be sedated by controlling the unit cost (between surface dressing –being minimal treatment, moderate overlay, deep inlay and reconstruction being maximal treatment) and treatment types. The approach delivered by the strategic model enables AM decisions on the prioritisation of the maintenance activities to be conducted. Other areas that are supported are the selection and evaluation of the replacement actions as well as the appropriate time for an intervention. The most viable type of intervention and optimal inspection plans and maintenance intervention is also justifiable.

Table 7-12 Cost Estimation for the Predicted Cost

Band **Repair Type**	**G**	**F**	**P**	**VP**
Dressing	$T_2$1 £228,072	$T_3$2 £342,108	$T_4$4 £456,144	$T_5$7 £570,180
Overlay	- -	$T_3$3 £1,006,200	$T_4$5 £1,341,600	$T_5$8 £1,677,000
Inlay	- -	- -	$T_4$6 £2,253,888	$T_5$9 £2,817,360
Reconstruction	- -	- -	- -	$T_5$10 £4,024,800

7.6 SUMMARY

The cost optimisation results obtained for the strategic deterioration model using the analytically formulated approach portrays that the best optimal value which can be altered as desired is obtainable depending on the CS of treatment intervention, expected performance level and the anticipated forthcoming performance condition. Cost effective decisions can help manage a high level of investment as it is the aspiration for every asset owner. Sound cost and resource decision making by asset managers is essential for the sustainability of the highway network. Better highway investment decisions and choices can be decided from knowledge generated from strategic cost models. The strategic model application enables asset managers to consider investments that require a higher initial investment but ought to yield lower cost and risks and higher performance over the asset lifecycle. By considering the various cost scenarios and strategies; it is possible to select an ideal price to renew the system to an optimal steady state. Cost estimations and effective planning are necessary for a sustainable highway network. The evaluations are useful in the determination of future budget allocation and prioritisation as presented using the strategic cost model. The cost model and others developed in literature are helpful in making a strategic level planning decision.

The knowledge of the way the assets deteriorate over time is expressed by the changes in performance conditions which help reveal how the degradation would affect the maintenance and rehabilitation cost and the risk to the users. These insights are very helpful to asset owners, managers and highway engineers in their maintenance decision making process. This significant advantage of the strategic cost optimisation method is its benefit to asset managers. The strategic model gives asset stake owners the insight into the implication of the several scenarios. The approach depicts the scenarios that each repair level action can have on the future performance and upcoming asset maintenance. On the other hand, the cost optimisation approach helps investigate current and forthcoming funding required to define a level of regular service and ideal performance condition practically. Moreover, and finally, the whole life cost of the assets is minimised as well preserved in a more efficient way using an analytical cost optimised approach due to the known identified scenarios of funding required.

CHAPTER 8: DISCUSSION, IMPACT of STUDY and FUTURE WORK

8.1 DISCUSSION

Sustainable development of highway infrastructure balances the essential needs for countries to achieve social, economic and environmental objectives of its transportation policies. Highway infrastructure systems are designed to have a long-term impact, hence, the necessity of a comprehensive maintenance programme to appraise their reliability, availability, maintainability and safety. This thesis reviews global level highway infrastructure maintenance and management on how its application can improve the decaying and newly created highway infrastructure in the surface transportation sector in Nigeria. Millennium Development Goals a build-up and expansion towards Sustainable Development Goals (SDGs) have failed in Nigeria, a West African country, reducing the economic and social benefits with increased environmental impact. Suitable and mature processes such as the UN Commission on Sustainable development is currently not fully employed in Africa, thus affecting their highway infrastructure maintenance and asset management practice.

Development of appropriate risk and reliability-based maintenance pointers are evaluation tools that provide benefits that the highway industry in Africa especially Nigeria is yet to annexe. Highway infrastructure performance tracking and comparison towards chosen SDGs wholly associated with international standards are discussed in this report. These preferences when introduced would convey better social and economic values with minimal environmental impact promoting a safe, stable, healthy and cost-effective highway infrastructure systems and networks. Functional failures and structural deterioration defects are amongst the leading causes of growing failure probabilities of the road systems and networks. Thus, asset maintenance intervention is an essential task for the unified management of road assets and systems.

The aim and objectives of this research are to consider risk and reliability-based probabilistic approach established on functional failure mode, effects and criticality analysis, parametric reliability analysis, risk-based assessment and strategic asset deterioration decisions. The combined continuous assessment frameworks and algorithms-based procedures utilise service inspection, safety inspection and survey inputs. The proposed reliability maintenance-based methodologies expressed in Figure 8.1 offers sustainable asset management for highways transport infrastructure and systems with emphasis on resolutions to their functional failures, defect-related risk and appropriate deterioration treatment.

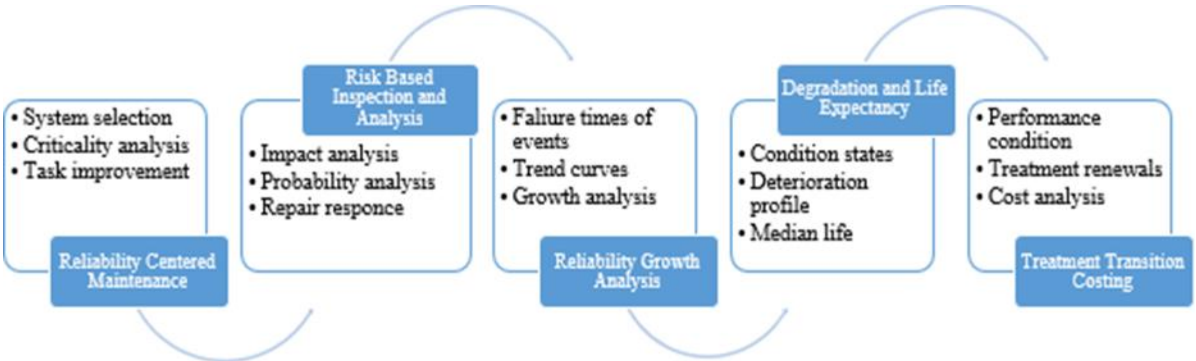

Figure 8-1 Proposed reliability-based maintenance methods for asset sustainability

Amongst the drive of a reliability-based maintenance practice for a sustainable transport asset management is the developmental support highway infrastructure brings providing the base for essential services a vibrant economy requires. However, managing highway infrastructure in ways that it serves the economy, reliable, safe to the user and cost-effective to infrastructure owners is a challenge. The functional failure and gradual deterioration of road assets are very precarious to an economy surface transportation with its effect diffusing throughout its entire networks. The results of highway assets in their weak condition with continuous functional failures lead to increased operating cost, longer travel time and damage to the vehicle to road users. The unavailability of highway assets not only account for high accident rates but also are considered originators of most traffic congestion and accidents (Department for Transport and Highway Agency, 2015). The highway assets of the road network often handle more traffic than they are often designed for, therefore requiring a sustainable asset management system. This chapter section concludes the approaches proposed to achieve risk and reliable based maintenance tactics to asset management with consideration of sustaining highway assets and infrastructure.

A comprehensive discussion and analysis have been conducted on highway infrastructure reliability application, risk mitigation, deterioration and strategic cost optimisation process in this research. The main findings and recommendations for risk and reliability-based maintenance for a sustainable highway infrastructure are summarised in this chapter. The important outcome of the research is to predict more accurate, practical and realistic risk-reliability optimisation of fielded highway assets. The research study was initiated with a background study on the importance of highway infrastructure asset maintenance and its problems with a focus on CAT 2 defect failures in Chapter 1. The research aims and objectives, research methodology and research key significance with research contributions were then presented. This study is sustained in Chapter 2 with an ample literature review on highway infrastructure asset maintenance, current methods used in AM of physical and networked systems. Other areas discussed are the framework of AM, assessment systems of asset condition with an insight into the various rating processes and their applications. The various types of inspection and surveys were also discussed to give a deeper understanding of the appropriate data sets to employs in the research work. Maintenance evolution, philosophy and the various PM types were also captured. RBM and reliability analysis were also discussed in addition to modelling performance and uncertainty of physical assets. The subsequent Chapters 3 to 7 consisting of the research methods and applications uniqueness and presented below accordingly.

The Chapter 3 of the research work focuses on how the use of RCM can support the development of PM strategy for newly installed fielded highway asset. Forecasting of PM planning strategies (***Objective 1***) using a decision logic to analysis functional failure modes of highway asset using a Cased Based Reasoning technique has been presented. The RCM presented establishes a qualitative relationship between the functional failure of the asset and the proposed maintenance strategy. The results obtained from the case study analysis portrays how the FMEA and decision logic method can be used to propose different PM strategies based on the eight critical questions which include the impact of PM measure on system reliability. The application of RCM strategies helped to decrease the number of failures consequences, controlling inadvertent stops, directing resources for timely detection of a failure in high impact assets. All functional failure, failure mode and their effect and consequences were considered when selecting appropriate maintenance task during their operating context. The classic RCM methodology introduced ensured that a criticality analysis was carried out for assets with hidden failures and strategies put in place to avoid functional failure of the assets and mitigate risk.

An RBI method was introduced in Chapter 4 to capture the MTTR in a stochastic environment. The utilisation of applying an RBI approach to defects on highways assets was based on the technical foundation provided from existing procedures of a risk-based approach. The RBI approach was able to overcome the precincts of the basic risk practices in literature as the inherent risk practices lack the flexibility to respond to demands by prescriptive rules and standard that is addressable by risk-based reliability methodology. The RBI intertwined with reliability in the stochastic application offered a systematic and coherent pattern for dealing with risk variations and standards. The MTTR were accurately estimated from real-time fielded data using reliability formula and conception of asset operating condition. An RBI –STOC algorithm was developed to analyse the risk assessment for CAT.2 identifying the defects that have reached the level of investigation. The impact/consequences of the risk occurring and the probability/likelihood of occurrence in configuration with standardised risk register are identified in the approach.

The average MTTR interval for CAT.2 defects are calculated, and their interval means (average repair for different defect categories) and standard deviation for all three classes of CAT.2 defects are generated. The MTTR maintenance interval outcomes of the defective periods about the defect categories based on the RBI and STOC analysis are generated. The precise MTTR intervals generated via the probability distribution using a bootstrap sampling propose the recommended MTTR interval. The MTTR and PDF provide better inspection interval regimes in consideration of the results from the MTTR-PDF outcomes. The RBI-STOC approach proposes reclassification of repair response interval ***(Objective II)*** for highway asset defect CAT2 defect, appropriate maintenance task response and efficient maintenance prioritisation of highway assets in equivalence with a contribution to system average MTTR and downtime.

Although the RCM strategy achieved the maintenance interventions predictions for highway assets via FMECA, quantitative judgements on the MTTF and MTBF were not captured as RCM is more of a qualitative approach, thus the introduction of an RGA and curve modelling in Chapter 5. The application of reliability growth methodology proved to be a potential tool that supported the in-depth reliability assessment of highway system for PM modelling and management. Analytical issues regarding the failure time of events of a system were determined by reliability growth methods countering assumptions that are often gotten from planning curves. The importance of Chapter 5 on reliability growth for the fielded system was crucial as little is known about any newly commissioned system. The growth curves output developed are useful in obtaining parameters central to the utilised entreated reliability growth model. The growth models support forecasting capabilities and combined reliability assessment over operation events to attain the current reliability level of fielded assets ***(Objective III)***. Reliability behaviour of highway asset is assessable using reliability estimates of it MTTF for instantaneous failure time of the event and MTBF for cumulative times of events. The prominent relationship between the Duane and Crow-AMSAA model in their observed cumulative MTBF and cumulative test logarithm was captured in their linear association and extended towards their failure intensity and cumulative failures. Also, the growth trend and parametric growth curves of HPP and NHPP power law are presented using MLE and LSE as well as their computed MCF of failure times of events. These reliability growth curves approach would support asset maintenance intervention being an essential task for the unified management of road systems.

A probabilistic maintenance model that links maintenance and reliability for describing the impact of gradually deteriorating highway asset is discussed in Chapter 6. The framework allows for the deterioration modelling of highway assets on the road network to aid highway authorities in road maintenance funding and policy decisions ***(Objective IV).*** The future of the road network condition can be modelled based on funding levels available to road authorities using the algorithms in this chapter as its predictions offer a charter to estimate the total maintenance budget requisite of the road network in a forthcoming year. A linear Markovian model for estimating the remaining life of the highway infrastructure developed in this chapter was obtained from real-time analysis of two successive inspections from the SCANNER survey of the UKPMS. The developed model helps to accurately define CS and predict the FS of highway infrastructures been considered crucial for developing appropriate inspection and maintenance regimes.

The Markov discrete probability model can predict more than one performance level using a constant transition probability matrix. The model which is considered useful for newly created as well as existing highway infrastructure consists of LTP matrix technique and an ML expectancy algorithm, both of a Markov Chain based deterioration modelling. The applicability of the model which was demonstrated with a case study using real-time carriageway inspection data set applies to other highway assets since they naturally lend themselves to being modelled at a group level due to their homogeneity. The simulated LTP predicted conditions was portrayed in a deterioration profile and a pairwise correlation while the MLs are computed with a CDF plot. Equally, any anticipated deviation to maintenance policy can be considered by strategically modelling the end product of these changes on future financial plan requirements and condition of the predicted road network as introduced in Chapter 6.

Cost effective decisions that help manage a high level of investment is the aspiration for every asset owner. Sound cost and resource decision making by asset managers is essential for the sustainability of the infrastructure network. Better highway investment choice is decided from known knowledge from optimised cost modelling. By considering the various cost options, it is possible to select an ideal cost to intervene with the optimal treatment. Cost estimations and effective planning are essential for a sustainable highway network. The estimations are useful in the determination of future budget allocation and prioritisation. The cost model would be helpful in making the strategic level planning decision. This significant advantage of the strategic cost optimisation model is the aid to asset managers on the insight of the implication the various scenarios can have on the future performance and asset maintenance requisite ***(Objective V).*** On the other hand, the cost optimisation approach can investigate current and forthcoming funding required to define a level of regular service and performance condition practically. Moreover, finally, the whole life cost of the assets is minimised as well preserved in a more efficient way using an analytical cost optimised approach due to the known identified scenarios of funding required.

8.2 IMPACT of STUDY

The proposed methods are a simplified approach which can be used as an analytical tool for concerned decision makers for maintaining new and existing highway infrastructures. The methods presented in the research enable highway asset owners, and managers to develop reliability-based maintenance strategies for strengthening and rehabilitating their newly created and already existing fielded highway infrastructures. In the maintenance of fielded highway assets, multiple maintenance methodologies are to be taking the applications. Precise predictions of asset deterioration and reliability-based management of highway systems can help engineers and managers to obtain a cost-effective strategy for the maintenance of highway systems. The approaches developed for the asset retention in this research are in themselves valuable means for maintenance engineers, managers, and asset owners.

The methods are useful in determining appropriate maintenance type and time, thereby creating an excellent platform for decision making. The proposed maintenance strategy can enable policymakers to select appropriate renewal methods based on the identified time to renew, repair or replace their highway infrastructure. The methodology and processes developed in the paper can support the organisation in enhancing its well-established maintenance programmes. The methods are organised to follow the generalised principle of reliability-based maintenance and should allow asset managers to implement them impeccably in conjunction with their existing processes.

8.3 RESEARCH CONTRIBUTIONS

This research work on the risk and reliability-based maintenance for sustainable highway infrastructure asset management added some valuable and specific general contribution to the knowledge in the field of highways infrastructure maintenance and management. The contributions are as follows:

- Demonstrated that instituting a problem-solving approach, scheduled PM can be developed for newly created infrastructure using the classical RCM.

- Established the reclassification of CAT2 failure repair interval from the actual real-time of 5days for CAT2H instead of standard 7 days and 41days for CAT2M instead of standard 28 days via an RBI-STOC approach.

- Demonstrated two reliability techniques using NHPP and HPP via estimation comparison respectively to ascertain appropriate deterioration growth trends of a fielded system.

- Established a linear transition technique and procedure to predict the deterioration and ML of highway asset deterioration.

- Developed strategic cost model with dual effects on treatment and performance transition for an optimised decision making.

8.4 RESEARCH LIMITATIONS and NEEDS

There are some limitations to the research work. Frankly articulated, there is no one way to evaluate and improve the maintenance and reliability of fielded highway infrastructure. The lack of resources for data collection is the key limitation of the research study. The research constituted 3 types of data set i.e. (i) Information generated from UK Highway Code of conducts on inspection and maintenance. (ii) Data on failure and maintenance history stored in UK NMMS generated via Detailed Visual Inspection (DVI) and (iii) Data of carriageway condition from SCANNER survey generated via a high-speed surface condition vehicle. The limitations of the data collection process in the research were inevitable. The need for better information management of highway asset data. The key limitations about the dataset were that the researcher was not in total control of the collection process as its time consuming and expensive in generating new dataset considering the disparate systems of the road network. Since the data set was not collected by the research team, the collection process could not be designed to meet our need. It was difficult to accurately analyse the data as it was not collected directly by the research team making the dataset difficult to understand and address the research questions. The data used in the research could have been collected for other purposes, this could have been interpreted differently than how we have interpreted it in our research group. Nevertheless, the on-site NMMSs and SCANNER has the information required to evaluate and improve the maintenance and reliability of these fielded highway assets studied in the research.

8.5 RECOMMENDATIONS and FUTURE WORK

The study presents some areas for further investigation. This report introduced the application of risk and reliability-based maintenance strategies and models for highway assets failures and deterioration, providing a solid underpinning with the future contextual studies into road infrastructure network maintenance, the following recommendation and future works are proposed.

- Multiple assessment criteria model which supports ease of data collection and use for roadway authorities with the ability to defines methodologies for roadway network inventory. This should be explored as it will help support highway assets in Nigeria with regards maintenance needs identification; road condition modelling; life cycle costing; and project benefit quantification. A case study of highway failure data collection prioritisation using a well-grounded international-based roadway authority should be introduced with a focus on the application in developing countries.

- It would be advantageous and ease of use to highway engineers and managers to generate modelling graphical user interface which can make use of the multiple risks and reliability-based maintenance models proposed in the research work as most available highway asset management and management in Nigeria are single focused towards reactive maintenance.

- The focus for investments in surface transport infrastructure (such as roadways) particularly in developing countries such as Nigeria should shift from the creation of new highways to the repair, rehabilitation and upgrade of existing ones. This proposed approach is if considered could ensure that long-established roadway networks are in conditions to provide uninterrupted services towards growing economic and social activities.

- A Criticality-Based Maintenance model that guarantees adequate utilisation of limited budget in project prioritisation ensuring that investments and potential benefits are appropriately quantified requires investigation. Increasing budgetary constraints and reduced allocation of funding improvement projects would require an effective evaluation method to assess reasonable expenditures allocated for highway network whole lifecycle management.

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