Estimation of Pavement Damage Cost for Establishing Equitable Road Use Fee for Commercial Vehicles – An Exploratory Empirical Analysis

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Sunbal Hanif
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National Institute of Transportation (NIT)
School of Civil and Environmental Engineering (SCEE)
National University of Sciences & Technology (NUST)

Sector H-12, Islamabad, Pakistan
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Certified that the contents and form of thesis titled "Estimation of Pavement Damage Cost for Establishing Equitable Road Use Fee for Commercial Vehicles – An Exploratory Empirical Analysis" submitted by Sunbal Hanif have been found satisfactory for the requirement of the degree.

Supervisor: _______________________________
Associate Professor (Dr. Anwaar Ahmed, PhD)

To my parents, my beloved siblings
and my dear friends

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LIST OF ACRONYMS

ACE	Associate Consulting Engineers
AASHTO	American Association of State Highway and Transportation Officials
BRTA	Bangladesh Road Transport Authority
CSIR	Council for Scientific and Industrial Research
DPHW	Department of Public Highway and Works
DFT	Department for Transport
ESAL	Equivalent Single Axle Load
ESP	Economic Survey of Pakistan
EUAC	Equivalent Uniform Annual Cost
FHWA	Federal Highway Administration Authority
GDP	Gross Domestic Product
GOP	Government of Pakistan
GVW	Gross Vehicle Weight
HGV	Heavy Goods Vehicles
JICA	Japan International Coordinate Agency
LCV	Longer Combination Vehicles
MAPE	Mean Absolute Percentage Error
MOC	Ministry of Communication
MPDC	Marginal Pavement Damage Cost
MR&R	Maintenance, Rehabilitation and Reconstruction
MOI	Ministry of Industries
MRTH	Ministry of Road Transport and Highways

NHA	National Highway Authority
NTRC	National Transport Research Centre
OLS	Ordinary Least Square
PTPS	Pakistan Transport Plan Study
PASW	Predictive Analytics Software
PDC	Pavement Damage Cost
TRRL	Transportation Road Research Laboratory
TRR	Transportation Road Record
TRB	Transportation Research Board

ABSTRACT

Due to higher user expectations and growing travel demand, highway agencies around the globe continue to face ever-greater needs for funding the maintenance, rehabilitation and reconstruction (MR&R) of their highway infrastructure. Highway agencies strive to charge road use fees that are based on actual share of infrastructure damage occasioned by different vehicle classes. Current road user charges (highway toll) for commercial vehicles in Pakistan are based on expert opinion, thus completely disregarding equity impacts. Present study used a rational framework by incorporating the actual maintenance strategies used by national highway authority (NHA) for estimation of pavement damage cost. MR&R strategies (treatment types and timings) were formulated using twenty-five year life-cycle length and standard maintenance and rehabilitation treatments used by highway agency. Marginal pavement damage cost (MPDC) for unit traffic loading was estimated by relating the highway agency pavement MR&R expenditure to the level of pavement loading. MPDC for national highway system (NHS) was estimated to be Rs. 0.395 (2014 constant Rupees) per ESAL-km. Present study also compared the road use fee based on MPDC with existing toll fee for major truck classes. The sensitivity of MPDC with respect to the pavement life-cycle length and interest rate was evaluated. Also, the impact of the accuracy of estimating the pavement reconstruction and rehabilitation treatment cost on MPDC estimates was investigated. A general comparison of individual axle load limits of Pakistan with selected countries was also carried out. The framework developed in this thesis can be used by NHA for carrying out a detailed study at national level to establish or update road user charges (toll rates) for both national and non-national highway networks.

CHAPTER 1. INTRODUCTION

1.1 Background

In recent years pavement damage due to overloading by heavy commercial vehicles has become a serious concern to national highway authorities. According to National Transport Research center (NTRC) “Load Axle Survey report of 1982”, 83% loaded vehicles exceed the legal axle load limits [Majeed,1982]. An estimate declares that, 70% of the two and three axle truck and 40% of four, five and six axle trucks are involved in overloading [MOI, 2007]. The damage caused by overloaded vehicles to the pavement is alarming. It was estimated by National Highway Authority (NHA) in 1995 that a two axle truck in Pakistan has twenty two times more damaging effect than a similar USA truck [PTPS, 2006].

Roads are the most important transport mean and Pakistan being an underdeveloped country has total road length of 260,000 kilometers (Km) including 8600 km national highways, 767 km motorways and 207 km strategic roads. NHA road network is 4.6% of overall road network but carries approximately 80% of commercial traffic. N-5 is considered as most important National highway for commercial traffic having a length of 1,819 km [PTPS, 2006]. The current estimates show that the reliance on roads as means of transportation has increased from 8% to 96% [ESP, 2012]. The trucking industry in Pakistan has yet not become modernized and still contains obsolete trucks which cause excessive damage to the pavement. According to a survey conducted by National Highway Authority (NHA) in 1995, the freight vehicle fleet dominated by two axle Bedford trucks containing 96% of total truck traffic. As the trucking industry started growing the obsolete Bedford trucks started to eliminate and reduction of 68.9% in two axle trucks has been observed [NHA, 1995]. National Highway Safety Ordinance (NHSO) - 2000 has set five, twelve, twenty two and thirty one tons as load limits on steering, single, tandem and tridem axles respectively but the set limits are not strictly enforced in the country and vehicles are overloaded due to truck operator’s quest to maximize profits [NHSO,2000].

The rapid deterioration of pavement due to overloaded vehicles causes economic loss to the country and increases the rehabilitation and maintenance costs while decreasing the pavement service life. According to “Pakistan Transport Plan Study -

2006" 50% of the NHA's highway network is in need of major rehabilitation and the rest 50% required adequate maintenance [PTPS, 2006]. Road Asset Management Division (RAMD) of NHA during 2004 – 05 pavement condition survey observed that 40% of the national road network was rated as either poor or of very poor condition [PTPS, 2006]. Recent estimate show that maintenance cost account for 25% of the total life cycle cost of road system. "NHA Annual Maintenance Plan 2012 – 13" estimates indicate that total toll revenue generated in the year 2012 – 13 was Rs 17.314 billion and it was insufficient to meet the increasing pavement maintenance expenditures (approximately Rs 28 billion annually) [NHA, 2012]. The overloading tendencies and rapid deterioration of pavements in Pakistan indicate that there is a need of a study at national level to quantify the pavement damage due to overloaded commercial vehicles and this thesis is the first step in this direction.

1.2 Problem Statement

Overloading by commercial vehicles is a common phenomenon in Pakistan despite set standards for legal axle load and gross vehicle weight limits [JICA, 2006]. Due to lack of appropriate enforcement and equitable fine structure, many trucks overloaded to the extent of dimensionless limits can be observed on major national highways. Overloaded vehicles not only result into premature failure of pavement but also results into excessive maintenance and rehabilitation cost. One of the major reasons for accelerated deterioration and unsatisfactory performance of pavements in Pakistan is overloading by commercial vehicles thus there is a need to quantify properly the share of damage cost among road users. The estimation of pavement damage cost is important for:

a. Evaluating current user charges
b. Designing equitable user charging system
c. Ensuring equity among user groups
d. Generating adequate revenue for damage repair

Specifically, there is need for the cost estimation of pavement damage for unit traffic load (ESAL) so that vehicle classes can be charged appropriately. However the challenges in estimating pavement damage cost for different vehicles classes are:

a. Lack of availability of reliable data from NHA
b. Inconsistent agency repair practices

1.3 Research Objectives

To overcome the overloading issues and to avoid rapid road damage in Pakistan, there is a need for reliable estimation of pavement damage cost. In order to address the key aspects of identified problem, the objectives set forth for this research are:

- To compare axle load limits of Pakistan with selected countries.
- To develop a simplified framework that incorporates MR&R policies for pavement damage estimation.
- To demonstrate the applicability of framework by estimating pavement damage cost for national highways of Pakistan.
- To carry out a comparison of existing road use fee and actual road damage being incurred by different vehicle classes.

1.4 Overview of Study Approach

A detailed methodology was devised to fulfil the research objectives, and the defined research tasks are as follows:

- Synthesis of the past research findings regarding pavement damage cost estimation (PDC) include both the international and national research efforts.
- Collection and collation of traffic and maintenance, rehabilitation and reconstruction (MR&R) cost data for Pakistan.
- Comparison of axle load limits of Pakistan with selected countries.
- Estimation of pavement damage cost (PDC) for Pakistan.
- Comparison of current road use fee and actual damage based on MPDC for different vehicle classes.

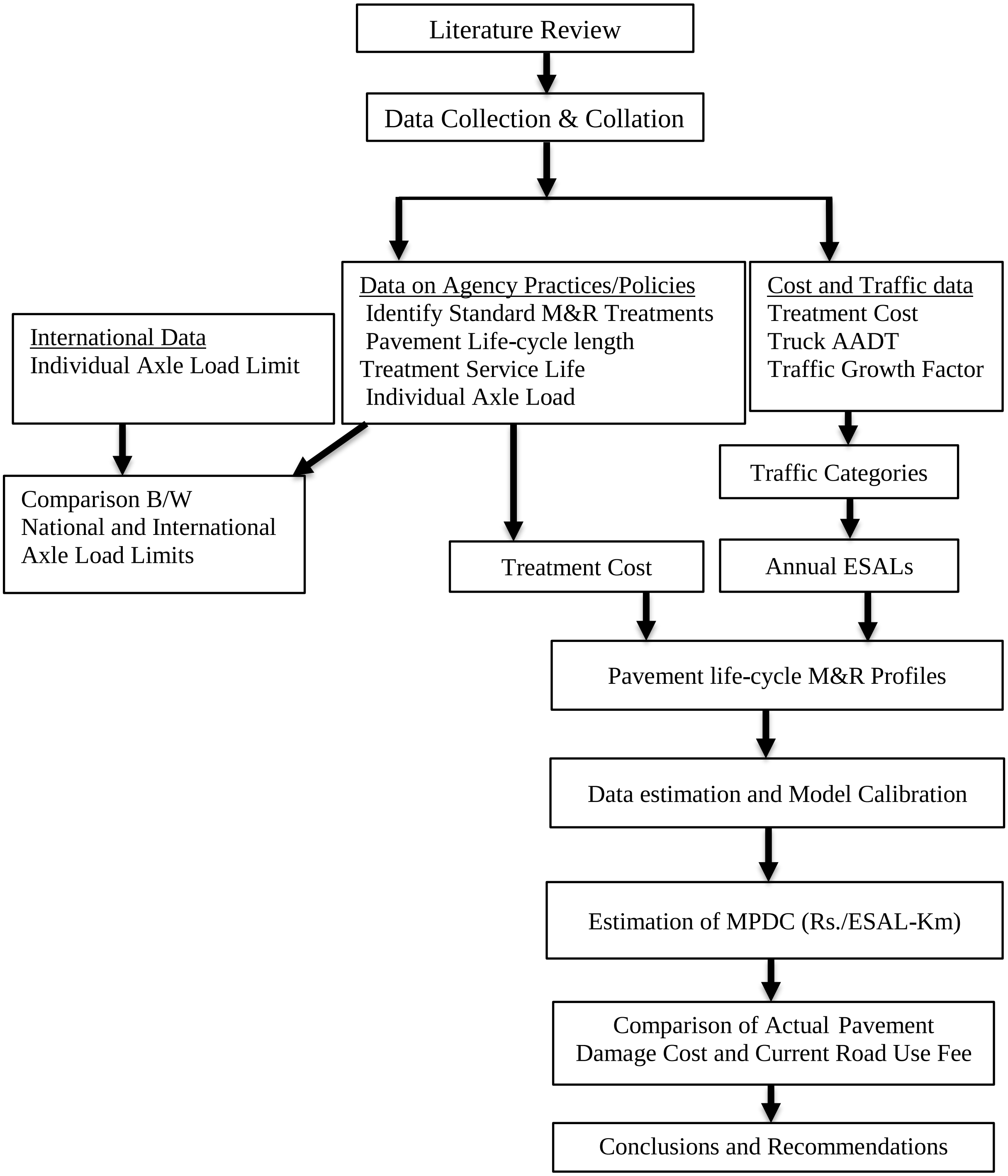


Figure 1.1 Overview of Study Approach

1.5 Thesis Organization

This study is structured into six chapters. Chapter 1 highlights the need for estimation of PDC and also study objectives are discussed. Chapter 2 provides a literature review on PDC estimation. Chapter 3 covers comparison of the individual axle load limits of Pakistan with selected countries. Trucking industry of Pakistan and overloading issues are also discussed in this chapter. MPDC estimation methodology, results and discussion are presented in chapter 4. Chapter 5 of this study includes the sensitivity analysis of MPDC using different variables. Lastly, Chapter 6 presents the research summary, conclusions, and recommendations.

CHAPTER 2. LITERATURE REVIEW

2.1 Introduction

This chapter covers the summary of international and national research studies which were carried out to quantify the pavement damage cost due to overloaded trucks. The chapter highlights the need of a proper methodology for estimating pavement damage cost for different vehicle classes. Literature review revealed that pavement damage costs (PDC) increases considerably due to the lack of weight limits enforcement. In developed countries, strict enforcement of laws and use of modern methodologies have contributed in lowering the pavement damage costs. There is no study carried out regarding the pavement damage cost (PDC) estimation in Pakistan while different studies have been carried out for the determination of equivalent single axle load (ESALs).

2.2 Highway Cost Allocation Studies

In past various study directions were used to allocate pavement damage to road users. Some of the studies carried out in the past were directed towards estimation of pavement damage cost (PDC) while others focused on highway cost allocation (HCA).

Highway cost allocation (HCA) is the distribution of repair costs among vehicle classes equitably and efficiently. Highway cost allocation studies includes a vast range of costs like major widening, construction, safety, management, Intelligence Transportation System (ITS) and environment. While for pavement cost allocation the costs included are: new construction, major widening, rehabilitation, maintenance and reconstruction.

2.3 Pavement Damage Cost Estimation Approaches

In the past studies two major approaches generally have been used for estimation of PDC: (1) Empirical approach and (2) Engineering approach. PDC includes only MR&R costs (reconstruction, rehabilitation, routine maintenance and periodic maintenance) which are directly associated with pavement structure. Empirical and engineering approaches are discussed in following paragraphs.

a. Empirical Approach:

This approach is based on real historical data collection on pavement repair and loading and then developing a statistical relationship between MR&R cost and predictor variables like traffic, climate, pavement type and pavement age etc. Then differentiate the developed function of cost with respect to pavement indicator like traffic loading to yield marginal pavement damage cost (MPDC).

b. Engineering Approach:

This is based on developing an expression for annualized cost of rehabilitation at fixed intervals for an infinite analysis time period as a function of traffic loading. The differentiation of annualized cost function with respect to annual traffic load will yield to MPDC.

2.3.1 Empirical Approach – International Research Efforts

Martin [1994] conducted a research study for Road Research Board of Australia for estimating load-related pavement maintenance and construction costs. The author developed separate models for total annual average maintenance cost, annual average routine maintenance cost and annual average periodic maintenance expenditures. The pavement age, traffic loading (ESAL), AADT, passenger car units and gross vehicle weight were used as independent variable. The author argued that heavy vehicles were responsible for 50% of the pavement maintenance costs. It was also concluded that 45% of expenditures related to pavement construction/replacement were load related.

Hajek et al., [1998] estimated marginal pavement damage due to trucks using Ontario data. In that study, cost functions were firstly obtained by regression analysis for new and in-service pavements. Then the estimated functions were differentiated to obtain the MPDC. The results indicated that MPDC highly depends on highway type. MPDC was estimated separately for new and in service pavements.

Ghaeli et al., [2000] studied the cost implications of different vehicle configurations and road characteristics based on the maintenance strategy used by Ontario Ministry of Transportation. That study used the Ontario Pavement Analysis of

Costs (OPAC) model to estimate pavement life cycle costs per ESAL-Km for 30 year analysis period. The analysis costs included the construction costs, reconstruction costs, maintenance costs and salvage value. The average maintenance and rehabilitation costs were obtained from Ontario Ministry of Transportation (OMT) for pavement life cycle analysis. A relationship was developed between life cycle cost and traffic loading for PDC estimation. The study concluded that trucks take the advantage from road system and need to share the cost of pavement damage.

Li and Sinha [2001] estimated the approximate load and non-load share of pavement damage cost. The authors developed ordinary least square (OLS) regression models to establish the function of highway costs and load and non-load related factors responsible for pavement damage. The models were estimated for different types of highways using rehabilitation only and rehabilitation and maintenance expenditures. Estimated models were differentiated to estimate the marginal maintenance expenditure. The study results revealed that PDC was highest for rigid pavements and lowest for flexible pavements.

Herry and Sedlacek [2002] estimated maintenance and rehabilitation marginal damage cost using data from Austria. The author developed a relationship between cost and traffic variables using OLS regression. The average MPDC was found to be 0.0017$ per VKm based on the developed model.

Ozbay et al. [2007] used the rehabilitation and periodic maintenance cost data from New Jersey for the year 2002 to 2004 for estimation of MPDC. The authors estimated the time between two resurfacing activities based on the annual number of trucks. MPDC was estimated in $ per vehicle as function of number of lanes, roadway length, traffic volume and time between two resurfacing activities.

Liu et al., [2009] estimated the pavement damage cost using the field from Kansas Pavement Management Information System (PMIS). The information on pavement minor and major rehabilitation was available but no data were available on routine maintenance. The truck vehicle miles travelled generated on the selected highway section were estimated. The researchers estimated the pavement damage cost in 2007 constant dollars using the systematic pavement damage estimation procedure that incorporated time decay and traffic related damage model developed by AASHTO. The study estimated PDC $1,727 per mile per year for the selected pavement section.

Ahmed et al., [2014] developed a framework that incorporates practical repair schedules for the estimation of MPDC. The author used the data from state of Indiana for estimating MPDC. The applicability of developed framework was demonstrated for the pavements of various age groups, different functional classes and surface types. The average MPDC estimated for interstate and non-national highways was $0.0032 /ESAL-mile and $0.1124 /ESAL-mile respectively. The study results concluded that with the increase in traffic and age, MPDC increases.

The summary of past international research on MPDC using empirical approach is presented in Table 2.1 below.

Table 2.1 Summary of International Research Efforts – Empirical Approach

Study	Methodology	Traffic Variable	Data Source
Martin (1994)	OLS Regression	ESAL	Australia
Hajek et al (1998)	OLS Regression	ESAL	Ontario (Canada)
Ghaeli et al (2000)	OPAC Model	ESAL	Ontario (Canada)
Li and Sinha (2001)	OLS Regression	ESAL	Indiana (1995-1997)
Herry & Sedlacek (2002)	OLS Regression	AADT	Austria (1987 -2004)
Ozbay et al (2007)	Non – linear model	ESAL	New Jersey (2004 -06)
Liu et al (2009)	AASHTO Equation	ESAL	Kansas
Ahmed et al (2014)	OLS Regression	ESAL	Indiana

2.3.2 Engineering Approach − International Research Efforts

Newberry [1988] presented the fundamental theorem and derived an expression to estimate MPDC for an overlay over an infinite analysis period. Some assumptions were made by the author like constant traffic, uniform pavement age, no weathering action during the selected life span for estimating MPDC. It was further assumed that an overlay activity will be performed when roughness reaches to a threshold value. The author estimated average MPDC for an additional ESAL considering roughness as performance indicator. Using data from Tunisia MPDC was estimated for overlays as $0.0013 – $0.0258/ESAL-Km.

Small et al [1989] extended Newberry's work by considering the effect of weathering and traffic. The MPDC models were estimated using present resurfacing cost as response variable and selecting traffic loading and pavement durability as explanatory variables. Using the results of a World Bank study titled "Road Deterioration and

Maintenance Effects", the author incorporated the effects of weathering. Small et al., determined the MPDC per Lane-mile for an infinite analysis time period using a discounted rate of 4% at a fixed time interval. It was concluded that weathering independently did not affect MPDC unless combined with axle weights but weathering make the road more vulnerable to damage by heavy loads.

Vitaliano and Held [1990] used the data of 475 roadway segments in New York to estimate MPDC. The author used a "theoretical" analysis to derive an expression for present cost of rehabilitation applied at fixed interval over an infinite analysis period. It was assumed in the study that traffic and climate contributes equally in pavement damage.

Lindberg [2002] estimated MPDC using data from "Swedish long term pavement performance program". The author used cracking as performance indicator and only considered the rehabilitation cost while ignoring climate effect. Estimated MPDC per ESAL-km varied from $0.0007 to $0.0176 for high strength and low quality highways. MPDC was estimated for combination trucks and passenger cars as 0.020$ per VKm and 0.0034$ per VKm.

Anani and Madanat [2010] presented a methodology which considered both rehabilitation and maintenance costs. The authors estimated MPDC using two interrelated activities: rehabilitation and periodic maintenance. It was assumed that maintenance activity occurred more frequently and it is less costly than rehabilitation. An expression was developed for the fixed repeating present value of rehabilitation and maintenance activity for an infinite analysis time. It was concluded that that those maintenance activities cannot be ignored which have less expenditures. It was also concluded that the interdependence of two activities: rehabilitation and periodic maintenance cannot be ignored.

The summary of past international research on MPDC using engineering approach is presented in Table 2.2.

Table 2.2 Summary of International Research Efforts – Engineering Approach

Study	Methodology	Traffic Variable	Data Source
Newbery (1988)	Rehab cost, Non-linear cost model	ESAL	Tunisia
Small et al (1998)	Rehab cost, Non-linear cost model	ESAL	USA
Vitaliani & Held (1990)	Rehab cost, Non-linear cost model	ESAL	New York
Lindberg (2002)	Rehab cost, Non-linear cost model	ESAL	Sweden
Anani &Madanat (2010)	Rehab and periodic maintenance cost, Non-linear cost model	ESAL	California

2.4 PDC Estimation – Miscellaneous International Research Efforts

Roberts and Djakfar [2000] investigated the effect of increasing gross vehicle weight (GVW) limits for Louisiana type 2 and type 6 vehicles hauling sugarcane, rice, timber and cotton on pavement rehabilitation costs. Data for pavement design and rehabilitation projects were secured from Louisiana department of transportation and Development (LaDOTD) database. Then, the payload for each truck travelling on the selected roadway was determined under each of the weight scenario. The 1986 AASHTO design procedures were used for the calculation of overlay thickness for the most recent rehabilitation. Author computed present worth (PW) of the rehabilitation cost for each weight scenario. It was concluded that increasing the GVW for vehicles operating at roads of less designed thickness will shorten its service life. Ultimately, the user costs will increase due to increase in GVW of vehicles.

Dodoo and Thorpe [2004] in their study argued that introduction of electronic on-board system including the components responsible for estimating pavement damage will assist charging heavy goods vehicles (HGV) more efficiently and equitably. The authors suggested an electronic method of charging HGVs based on dynamic axle weights, no of axles and distance travelled are the main parameters of proposed systems.

Salama et al., [2006] urged that there is a need to examine the new truck configurations and their effects on pavements using the field performance data. That study focused on investigating the damage due to multiple axles on flexible pavements in terms of cracking rutting, and roughness. The author used the real field data from the state of Michigan for the analysis. In addition, traffic data along with truck configurations and weights were extracted from Federal Highway Administration (FHWA) website. The authors used simple, multiple and stepwise regression techniques. It was concluded that single and tandem axles have more cracking damage than those of multiple axles. In the contrary, multiple axles cause more rutting on flexible pavements than single and tandem axles.

Zhang et al., [2007] investigated the effect of changed traffic and environmental conditions on American Association of State Highway and Transportation Officials (AASHTO) load equivalence factors (LEFs). Furthermore, a performance based fatigue model was also developed using AASHTO LEFs. It was also reported that the developed model can be used for different traffic and environmental settings.

Timm at al., [2007] studied the impact of site specific load spectra on flexible pavement using Mechanistic Empirical pavement design procedures. The author considered 12 site specific load spectra in Alabama. Mechanistic Empirical pavement design procedures, Monte Carlo simulation and transfer functions were used to generate the pavement performance distributions, considering a three layered structure. Load repetitions to failure were then predicted using transfer functions and then required pavement thickness was determined.

Peters and Timm [2008] estimated the damaging effect of increasing the weight limits by the change in axle configuration from tandem to a tridem axle. Mechanistic Empirical Pavement Design Guide (MEPDG), a layered elastic pavement program was used for the analysis. The no of load repetitions to failure were calculated as a function of strain and modulus values. It was observed that form the investigation that strain values for tridem axles were slightly less than tandem axles.

2.5 PDC Estimation – National Research Efforts

Majeed [1982] synthesized National Transport Research Center (NTRC) axle load study of 1982. The main focus of the study was to evaluate the extent to which the vehicles are overloaded in Pakistan. A survey was carried out across all the main roads in Pakistan and thirty five road segments were selected for this purpose. The vehicle weight data were collected for twenty four hours and three to four times in a year, covering a total of 31,746 commercial trucks.

The ESAL for different vehicles were calculated using the legal axle load limits and 4.5 power law. It was observed that 83% of the vehicles exceed the legal limit of 18000 lb. Total ESALs for loaded and empty vehicles were found to be 3.3 and 1.2 respectively.

Associated Consulting Engineers [1988] conducted an axle load survey on Indus Highway (N-55), and seventeen stations were selected and a total of 2640 vehicles were surveyed. The ESAL values for loaded vehicles ranged between 0.814 for tractor trolley to 18.066 for four axle trucks.

Road Research and Material Testing Institute of Punjab highway Department [1989] conducted an axle load survey in 1989. The survey was carried out around the cities of Lahore and Faisalabad.

Transportation Road Research Laboratory, UK [1991] reported an overview on the performance and organization of Pakistan road freight industry. A survey which was carried out in 1985 and 1986 include the information about vehicle manufacture, fleet composition, and the role of freight agents towards costs, tariffs and the productivity of industry. The authors found that there is a high concentration of freight traffic along N-5 route. A road side interview survey was also conducted to collect information related to vehicle age, body, make, insurance, loads and accidents. It was examined that Pakistan freight industry mostly comprised Bedford trucks in 1970s and 1980s but later on modern type of trucks like Mercedes, Hino, and Nissan started dominating the industry. As a result of the road side survey percentages of different truck types were also estimated. It was also deducted from the survey results that industry was mostly run on hire and reward basis and very few consigners own the vehicles.

An axle load survey of Sheikhupura – Multan – D.G Khan Motorway was carried out in 1993 by National Engineering Services, Pakistan Limited [1993]. A total of 658 vehicles were surveyed, comprising two and multi axle vehicles. In the study that ESALs for two and five axle truck trailer were found to be 7.4 and 28.3 respectively.

In 1982 the first axle load study was accomplished by NTRC in Pakistan. Then for the purpose of updating the NTRC study and assessing the present situation NHA [1995] conducted a country wide axle load survey in 1995.

The survey was carried out on National Highway system and the data were collected on N-5, 25, 35, 40, 55, 65 and N-70. Commercial vehicles with two, three, four axles and more than four axles were considered for the survey. A total of 4768 trucks were surveyed. Two axle trucks were found to be 68.9% of this traffic volume while multi axle trucks were 31% including 22.7% three axle, 6.5% four axle and 1.9% of five axle trucks. In the study ESALs were estimate for loaded and empty trucks using AASHTOs power law based on 4.5 power of exponent. Average EASLs calculated for different truck configurations are presented in Table 2.4 as follows.

Table 2.3 ESALs Estimates for Different Truck Classes

Truck Class	Truck configuration	ESALs
Class 6	2 Axle (Steering + 1 × Single)	6.49
Class 7	3 Axle (Steering + 2 × Single)	18.48
Class 8	3 Axle (Steering + 1 × Tandem)	19.00
Class 10	4 Axle (Steering + 3 × Single)	17.30
Class 12	4 Axle (Steering + 1 × Single + 1× Tandem)	19.59
Class 18	6 Axle (Steering + 1 × Tandem + 1× Tridem	27.96

(NHA, 1995)

Associated Consulting Engineers (ACE) [2001] conducted a study for updating the design of additional carriageway of Bahawalpur section of N-5. A seven day traffic count was carried out on three segments of N-5 to classify the traffic stream into cars, buses, two, three, four, five and six axle trucks and tractor trailers. Then the traffic was projected to annual daily traffic using 5%, 6% and 7% growth rate. ESALs were then calculated for the three segments.

Rabia and Afsheen [2013] studied the impact of various truck axles on the pavement in Pakistan. In this study, WIM data were collected and analyzed from two stations located on Grand Trunk Road (N-5) between two major cities of Pakistan (Peshawar and Rawalpindi). Truck factors for different truck types were determined and the most damaging axle type in Pakistan was identified. Regression models were developed for numerous truck types to develop a relationship between truck factors and gross vehicle weight.

Table 2.4 Summary of Past National Research – Related to PDC

Ser.	Study	Year	Author
1.	Axle load survey report	1982	National Transport Research Center (NTRC)
2.	Axle load survey	1988	Associated Consulting Engineers (ACE)
3.	Axle load survey	1989	Road Research and Material Testing Institute (RR&MTI)
4.	An overview of Pakistan road freight industry	1991	Transportation Road Research Laboratory (TRRL) ,UK
5.	Axle load survey	1993	National Engineering Services of Pakistan (NESPAK)
6.	Axle load study on national highways of Pakistan	1995	National Highway Authority (NHA)
7.	Report on traffic study, axle load survey and pavement design	2001	Associated Consulting Engineers (ACE)
8.	Effects of variation in Truck factor on pavement performance in Pakistan	2013	Rabia and Afsheen

2.6 Chapter Summary and Conclusion

Overloading by heavy vehicles and resulting pavement damage has emerged a challenge for highway agencies around the globe. Every year millions of rupees are spent on more frequent maintenance and rehabilitation treatments of the pavements due to excessive loading and their premature failure. The major factors responsible for higher pavement damage costs (PDC) are: (1) increased GVW and (2) higher axle loads. Research findings indicate that improved pavement design and structure, enhanced regulations on truck weights and dimensions, better control on GVW and axle weights and proper implementation of regulations can help to lower the damage costs. There are very few studies undertaken by various leading organizations in Pakistan which give some information about country’s trucking industry and the damage in terms of ESALs. But there is no research work done at national level which addresses the PDC estimation and its allocation to different classes of vehicles.

CHAPTER 3. OVERVIEW OF TRUCK WEIGHT REGULATIONS IN PAKISTAN

3.1 Introduction

In this chapter, current situation of road infrastructure and existing truck weight limits are discussed. The chapter also gives an overview about the population, economy and road network growth in Pakistan. Furthermore, the existing truck configurations and weight limits in Pakistan are presented. Freight transportation and truck overloading issues in Pakistan are also discussed in detail. In the later section, weight limits of selected countries are discussed and finally a comparison with Pakistan with these countries is made.

In 1982, NTRC conducted axle load study for National Highways Board and Ministry of Communications (MOC) [Majeed, 1982]. In 1983 National Transport Study was done in corporation with JICA. NTRC carried out survey under a cooperative program with overseas unit of Transport and Road Research Laboratory, UK (TRRL) in 1985 and 1986 to gather information about truck configurations, vehicle weights, and role of freight agents and performance of trucking industry [TRRL, 1991]. In 1995, NHA carried out Axle load study on National highways [NHA, 1995]. In September 2000, the National Highway Safety Ordinance (NHSO) was passed to impose weight limits and control the overloading on highway infrastructure in Pakistan [NHSO, 2000]. Pakistan Transport Plan Study (PTPS) was conducted in 2006 with coordination of Japan International Coordination Agency (JICA) to update the information about transport sector of the country and for preparing the transport plans to fulfill the future needs of Pakistan [PTPS, 2006].

3.2 Freight Transportation in Pakistan

Roads are the most important mode of transport not only for people but also for freight transportation. Transport volumes on roads grew by 5% per year for passenger traffic and 12% per year for freight traffic in terms of ton-km form 1990s to 2006 [PTPS, 2006]. The current figures show that roads in Pakistan carry 92% passenger traffic and 96% inland freight and are the backbone of country's economy. However the reliance on roads since 1947 was only 8% but now it has jumped to 96% [ESP, 2012]. In contrast, Pakistan railways (PR) carries 5.46 billion ton-km of freight which is only 4.21% of total freight and has a total track length of 11,515 km. The freight transport has gradually shifted from rail towards roads (Figure 3.1) over the year 1991 – 2006.

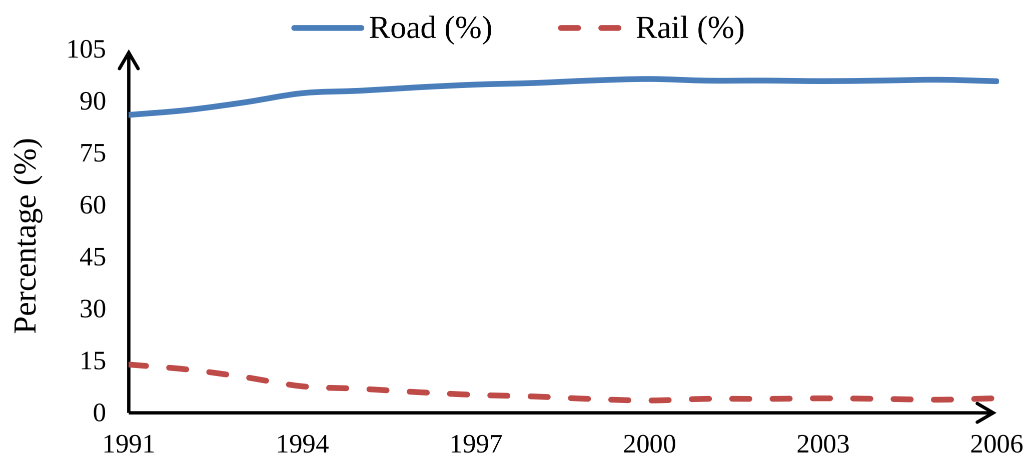


Figure 3.1 Trend of Road and Rail Freight Transport in Pakistan (PTPS,2006)

Road freight sector in Pakistan has major contribution to the GDP of the country but in spite of this fact the sector is informal and unorganized. There are very few owners in the sector who own a truck fleet of greater than ten vehicles. National Logistic Cell (NLC) is the only government body which owns and runs a large trucks and trailers fleet. Mostly, the truck units are imported and sold to individual truck operators. The inefficiencies of the freight sector has led to the economic loss of Rs. 150 billion per year including the cost of Rs. 25 billion per year for infrastructure deficit. [MOI, 2007].

3.3 Truck Configurations and Weight Limits in Pakistan

In 1970s and 1980s trucking industry of Pakistan was dominated by two axle Bedford trucks with a carrying capacity of seven ton and ninety eight horse power (hp) engine. Later on, Bedford trucks starts decreasing and demand for new trucks like Hino, Nissan, Isuzu, Benz and Mercedes introduced with two and three axles increased [TRRL, 1991]. A suggested classification for various truck configurations operating in Pakistan based on NHA and NHSO truck classification is presented in Table 3.1.

Table 3.1 Suggested Vehicle Classes and Truck Configurations in Pakistan

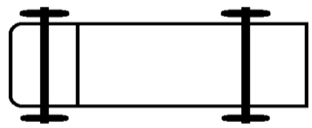
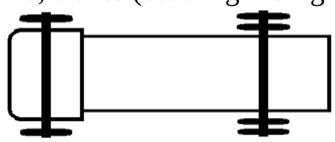
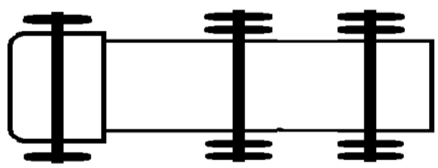
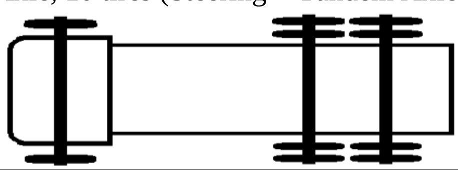
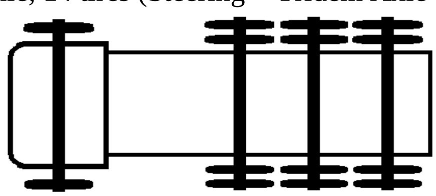
Vehicle Class	Configuration
Class 1 (Motor Cycle/Rickshaw)	2 Axle, 2 or 3 tires
Class 2 (Passenger Car)	2 Axle, 4 tires
Class 3 (Wagons and Buses)	2 Axle, 4 tires (Steering + Single Axle) 
Single Unit Trucks	
Class 4	2 Axle, 6 tires (Steering + Single Axle with dual wheels) 
Class 5	3 Axle, 10 tires (Steering + 2 * Single Axle with dual wheels) 
Class 6	3 Axle, 10 tires (Steering + Tandem Axle with dual wheels) 
Class 7	4 Axle, 14 tires (Steering + Tridem Axle with dual wheels) 

Table 3.1 Suggested Vehicle Classes and Truck Configuration in Pakistan (Continued)

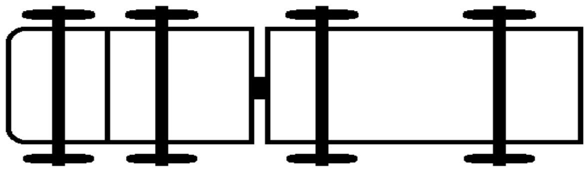
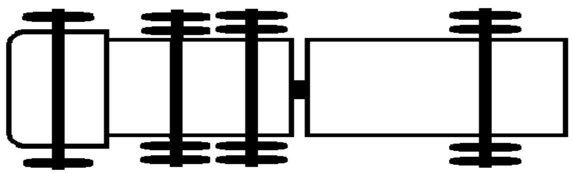
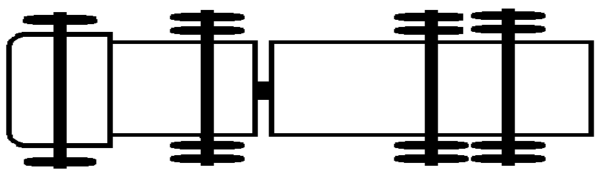
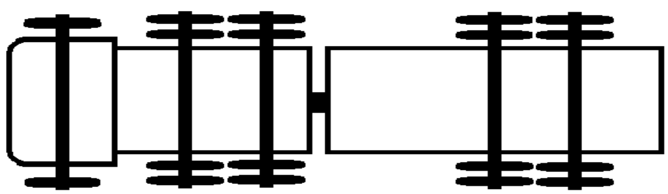
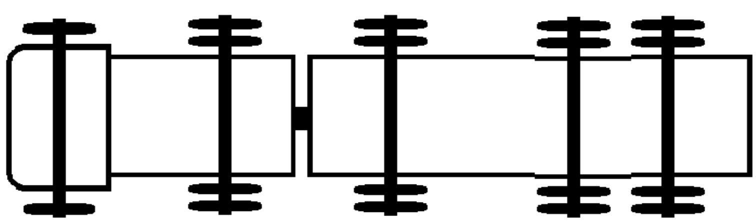
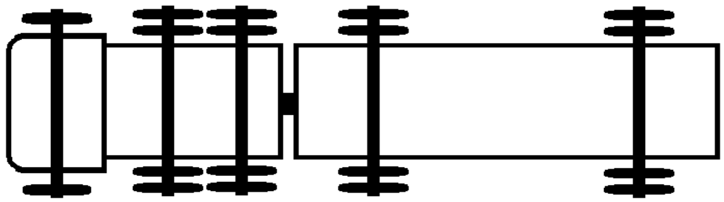
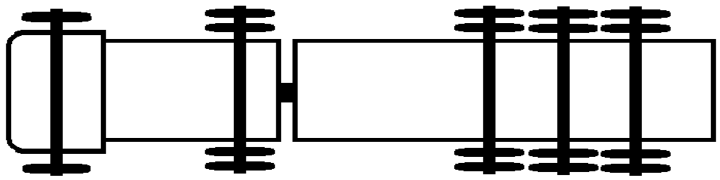
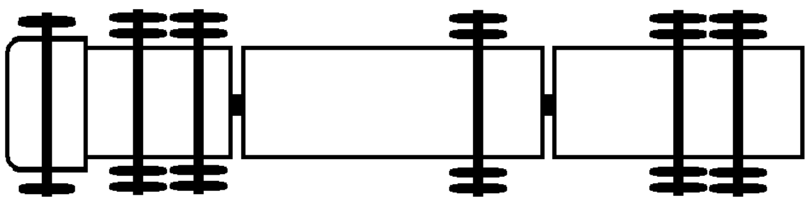
Vehicle Class	Configuration
	Multiple Trailers
Class 8	4 Axle, 14 tires (Steering + 3 * Single Axle with dual wheels) 
Class 9	4 Axle, 14 tires (Steering + Tandem Axle with dual wheels + Single Axle with dual wheels) 
Class 10	4 Axle, 14 tires (Steering + Single Axle with dual wheels + Tandem Axle with dual wheels) 
Class 11	5 Axle, 18 tires (Steering + Tandem Axle with dual wheels + Tandem Axle with dual wheels) 
Class 12	5 Axle, 18 tires (Steering + Single Axle with dual wheels + Single Axle with dual wheels + Tandem Axle with dual wheels) 

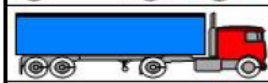
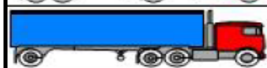
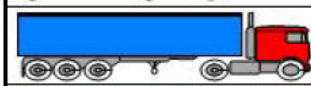
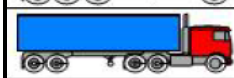
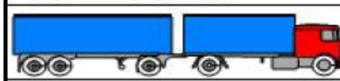
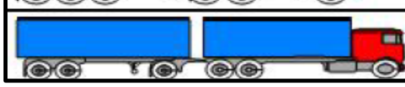
Table 3.1 Suggested Vehicle Classes and Truck Configuration in Pakistan (Continued)

Vehicle Class	Configuration
Class 13	5 Axle, 18 tires (Steering + Tandem Axle with dual wheels + 2 * Single Axle with dual wheels) 
Class 14	5 Axle, 18 tires (Steering + Single Axle with dual wheels + Tridem Axle with dual wheels) 
Class 15	6 Axle, 22 tires (Steering + Tandem Axle with dual wheels + Single Axle with dual wheels + Tandem Axle with dual wheels) 

(NHA, 1995; NHSO, 2000)

In order to regulate the truck weight in Pakistan, NHSO enforced GVW and axle weight limits in 2000. The configurations and allowable load limits imposed by NHSO are presented in Table 3.2 and 3.3.

Table 3.2 NHSO Allowable Gross Weight Limits in Pakistan

TRUCK TYPE		Permissible Gross Vehicles Weight (In Tons)
	2 AX SINGLE (Bedford)	17.5
	2 AX SINGLE (Hino/Nissan)	17.5
	3 AX TENDEM	27.5
	3 AX SINGLE	29.5
	4 AX SINGLE-TENDEM	39.5
	4 AX TENDEM-SINGLE	39.5
	4 AX SINGLE	41.5
	5 AX SINGLE-TRIDEM	48.5
	5 AX TENDEM-TENDEM	49.5
	5 AX SINGLE-SINGLE-TENDEM	51.5
	5 AX TENDEM-SINGLE-SINGLE	51.5
	6 AX TENDEM-TRIDEM	58.5
	6 AX TENDEM-SINGLE-TENDEM	61.5

(NHSO, 2000)

Table 3.3 Allowable Axle Load Limits in Pakistan

Axle Type	Allowable Load (Tons)
Steering Axle	5.5
Single Axle	12
Tandem Axle	22
Tridem Axle	31

(NHSO, 2000)

3.4 Trucking Industry and Overloading Issues in Pakistan

An efficient transport system and well-developed road infrastructure is very important for the economic enhancement of a country. As the major load of passenger as well as freight traffic is carried through road therefore it has become the backbone of Pakistan's transport system. In viewing the importance of road transport system, Government of Pakistan (GOP) has taken an initiative step of "National Trade Corridor Improvement Programme" (NTCIP) to improve the road infrastructure and logistic chain in the country. In April 2006, Engineering Development Board (EDB) circulated a detailed road freight strategy paper to the related stakeholders in order to develop strategy on "Modernization of Trucking Sector" in Pakistan. The number of registered trucks in Pakistan from 2000 to 2006 is summarized on Table 3.3.

Table 3.4 Total Registered Trucks in Pakistan

Year	Registered Trucks
2000	148,569
2001	157,027
2002	170,615
2003	178,883
2004	181,150
2005	183,962
2006	208,347

(MOI, 2007)

In order to modernize the trucking industry in Pakistan, it is very important to improve the Motor Vehicle Examination (MVE) and fitness system because unfit trucks are a source of accelerated wear and tear of road surface. Poor condition of suspension systems, axles, brakes and wheels represent an unfit vehicle. There are a total of eighty MVE posts present in the country. In Pakistan, Trans Freight Stations (TFS) are not available which can provide dedicated facilities for the movement of large trucks like rest areas for drivers, facilities to refuel, periodic maintenance of vehicle, workshops and outlets for Motor Vehicle Examination. The provision of modern facilities is necessary for bringing the trucking industry to international standards. There is a need of accredited training institutes for teaching and licensing of truck drivers which is an essential requirement to upgraded trucking industry. It is estimated that 80% truck drivers are unaware of recent regulations and systems and are proficient to drive old trucks. To modernize the present fleet composition there is an urgent requirement of standards and specifications regarding trucks and trailers at national level. Therefore, EDB constituted a committee and defined Standards and Specifications Draft of trucks and trailers for the first time at National level and forwarded it to Pakistan Standards and Quality Control Authority (PSQCA). The standards include (1) GVW, (2) power to weight ratio, (3) axle arrangement, (4) suspension system, (5) brakes and (6) dimensions of trucks and trailers [MOI, 2007].

NHA in 1995 calculated average ESALs for various axle configurations in accordance with AASHTO Design Guide and compared it with USA trucks. A two axle truck in Pakistan has twenty two times more damaging effect than a two axle USA truck [PTPS, 2006]. The Table 3.5 presents the ESALs comparison of two countries.

Table 3.5 ESAL Comparison between Pakistan and USA Trucks

Truck Type	Axle Configuration	Total ESALs	
		Pakistan	USA
2-Axle	Both Single Axles	4.67	0.21
3-Axle	One Single & One Tandem Axle	8.84	1.59
4-Axle	All Single Axles	12.99	1.32
4-Axle	Two Single & One Tandem Axle	10.35	1.32
5-Axle	One Single & Two Tandem Axle	14.73	1.39
6-Axle	One Single, Tandem & One Tridem Axle	10.90	1.39

(PTPS, 2006)

NHA has fifty four weighing stations to enforce the weight limits and control the overloading on National highways. A fine of Rs.100 Rs. per ton is charged for overloaded trucks but it is not followed strictly and the trucks are allowed to travel without paying fix fee because of the unavailability of parking space for overloaded trucks at weigh stations [PTPS, 2006].

3.5 Gross Vehicle Weight and Axle Load Limits − An International Overview

3.5.1 Truck Weight Limits – United States (US)

United States has total of 133,130,032 registered trucks [US Bureau transportation statistics, 2012]. Trucks are classified as single unit and combination trucks and account for 3.5% of the total vehicle fleet. Trucks having GVW between 10,000 pound and 26,000 pound are considered as medium and with more than 26,000 pound GV are termed as heavy duty trucks [Blower and Woodrooffe, 2012]. The trucks are classified according to FHWA's thirteen classes [FHWA, 2010]. The regulations to constrain the maximum weight limit and axle weight limits of common truck configurations are presented in the Table 3.6 as follows.

Table 3.6 Truck Weight Limits – USA

Configuration Type	Number of Axles	Maximum Weight (Tons)
Single Unit Truck	3 , 4	25 – 35
Semitrailer	5 , 6	40 – 50
STAA Double	5 , 6	40
B-Train Double	8	52.75 – 68.9
Rocky Mountain Double	7	52.75 – 64.5
Turnpike Double	9	52.75 – 73.5
Triple	7	52.75 – 65.5

(FHWA, 2010)

United States have set 9.1, 15.74 and 21.84 tons maximum permissible load limits for single, tandem and tridem axles respectively [FHWA, 2013].

3.5.2 Truck Weight Limits – South Africa

The regulations limiting the maximum permissible weight remains unchanged for many years in South Africa. Until March 1996, the maximum permissible load on a single axle with four wheels was 18,078 pounds (8,200 kg), a tandem (double) axle unit was limited to 36156 pounds (16,400 kg) and a tridem (triple) axle unit was limited to 46297 pounds (21,000 kg). Latest regulations regarding the maximum axle loads recommended by the Southern Africa Transport and Communications Commission (SATCC) are discussed in the following paragraph [CSIR, 1997].

South Africa has set axle weight limits for different types of truck configurations running in the country. The weight limits for single wheel, single axle with two wheels (non-steering), tandem axle unit with two wheels per axle are set as 4.40, 8.82, 17.6 tons.

Also, the load limits of 8.49, 9.92, 19.8 and 26.5 tons are set for steering, single, tandem and tridem axles [Bosman, 2006].

3.5.3 Truck Weight Limits – Canada

The first board legislation regarding truck weights and dimensions was passed in 1927 by Ontario in Canada. 1n 1954, Ottawa passed Motor Vehicle Transport Act (MVTA) to regulate the trucking operations for all the provinces and territories. The most commonly used configurations in the country are five and six axle tractor semitrailers and seven, eight axle double trailer combinations. Longer Combination Vehicles (LCVs) are also in operation in the country. LCVs in Canada are defined as tractor or trailer combinations with two or three semitrailers or trailers and having a total length more than twenty five meters [schulman, 2003].

The load limit for steering axle of tractor and trucks has been set as 6.06 and 7.99 tons while 10.03 tons has set for single axle with dual tires. The load limits for tandem axle with spread of 1.2 and 1.8 meter has been set by Canada as 18.74 tons. The load limits for tridem axle with spread of 3.0 and 3.7 meter has set as 25.35 and 26.46 tons [schulman, 2003].

3.5.4 Truck Weight Limits – India

In India trucks are classified as rigid, semi articulated and truck trailer combinations. The regulated maximum GVW limits on different types of vehicles in India are presented in Table 3.7 as follows.

Table 3.7 Vehicle Type and Maximum GVW in India

Vehicle Type	GVW (Ton)
Rigid Vehicles	
Two Axles with rear single	16.2
Three Axles with rear tandem	25.0
Four Axles with rear tandem	31.0
Semi-Articulated Vehicles	
Two Axle Tractor Single Axle Trailer	26.4
Two Axle Tractor (4 tires rear axle) Tandem Axle Trailer	35.2
Two Axle Tractor Three Axle Trailer	40.2
Three Axle Tractor (8 tires rear axle) Single Axle Trailer	35.2
Three Axle Tractor Tandem Axle Trailer	44.0
Truck-Trailer Combinations	
Two Axle Truck Two Axle Trailer	36.6
Three Axle Truck Two Axle Trailer	45.4
Three Axle Truck (4 tires rear axle) Three Axle Trailer	45.4
Three Axle Truck (8 tires rear axle) Three Axle Trailer	54.2

(MRTH, 1988)

The allowable load limits for steering, single, tandem and tridem axles in India are set as 6, 10.2, 19 and 24 tons respectively [MRTH, 1988].

3.5.5 Truck Weight Limits – Bangladesh

The weight limits on steering, single, tandem and tridem axles are implemented in Bangladesh by Bangladesh Road Transport Authority (BRTA). The axle load limits for steering, single, tandem and tridem axles are 5.5, 10, 16.5 and 19.5 tons respectively [BRTA, 2003].

3.5.6 Truck Weight Limits – China

There were 17,221,698 registered trucks in the China in 2009. Truck population is growing at a moderate pace with a share of 9 % in the vehicle stream. Trucks are classified as heavy, medium, light and mini. Vehicles having GVW of 10,000 pounds or more are considered as heavy and medium trucks representing 55-60 % of truck population and growing at a rate of 10 % annually [Blower and Woodrooffe, 2012]. All other trucks in the population are considered as light trucks. Ministry of communications and public security are responsible for applying the trucks weight limits and enforcement levels in China [Blower and Woodrooffe, 2012]. The weight limits of 6.6, 11.0, 19.8 and 24.2 tons are used for steering, single, tandem and tridem, axles to control overloading and prevent the country's road infrastructure [Wen et al, 2005].

3.5.7 Truck Weight Limits – Australia

The trucks in Australia are classified as articulated or rigid. Articulated trucks consist of a tractor and one or more trailers while rigid trucks have only a power unit with a cargo body. The truck fleet in the country contains three or four trailer combinations including double trailer trucks, road trains and B-doubles. Two trailer combinations and three axle tractor semi-trailers have gross weights of sixty three tonnes and forty one tonnes respectively [Blower and Woodrooffe, 2012]. The allowable axle weight limits in Australia for steering. Single, tandem and tridem are 6.6, 9.9, 18.2 and 22.0 tons respectively [Wild and Michael, 2002].

3.5.8 Truck Weight Limits – United Kingdom

UK has set weight limits for goods vehicles in the country to avoid roads wear and tear. A vehicle is considered overloaded when its axle weight or the gross weight exceed the plated weight limit mentioned by the manufacturer. The weight limits for steering, single, tandem and tridem axles are 11.0, 12.7, 17.6 and 23.1 tons respectively [DFT, 2007].

3.6 Comparison of National Axle Load Limits with Selected Countries

The allowable load limits on steering, single, tandem and tridem axles in Pakistan are compared with selected countries. The comparison of axle load limits with selected countries is presented in Table 3.8.

Table 3.8 Comparison of National Axle Load Limits with Selected Countries

Axle Load (Tons)				
Country	Steering	Single	Tandem	Tridem
Standard	5.46	8.19	15.47	21.84
Pakistan	**5.50**	**12.0**	**22.0**	**31.0**
US	5.46	9.10	15.47	21.84
South Africa	8.49	9.92	19.8	26.5
Canada	7.90	10.0	18.7	25.3
India	6.00	10.2	19.0	24.0
Bangladesh	5.50	10.0	16.5	19.5
Australia	6.60	9.90	18.2	22.0
UK	11.0	11.02	17.6	23.1
China	6.60	11.0	19.8	24.2

The comparison of single axle load (Figure 3.2) revealed that load limits of three countries exceed the average axle load limit. It was also revealed that axle load limit of Pakistan is higher than the average single axle load of 10.14 tons.

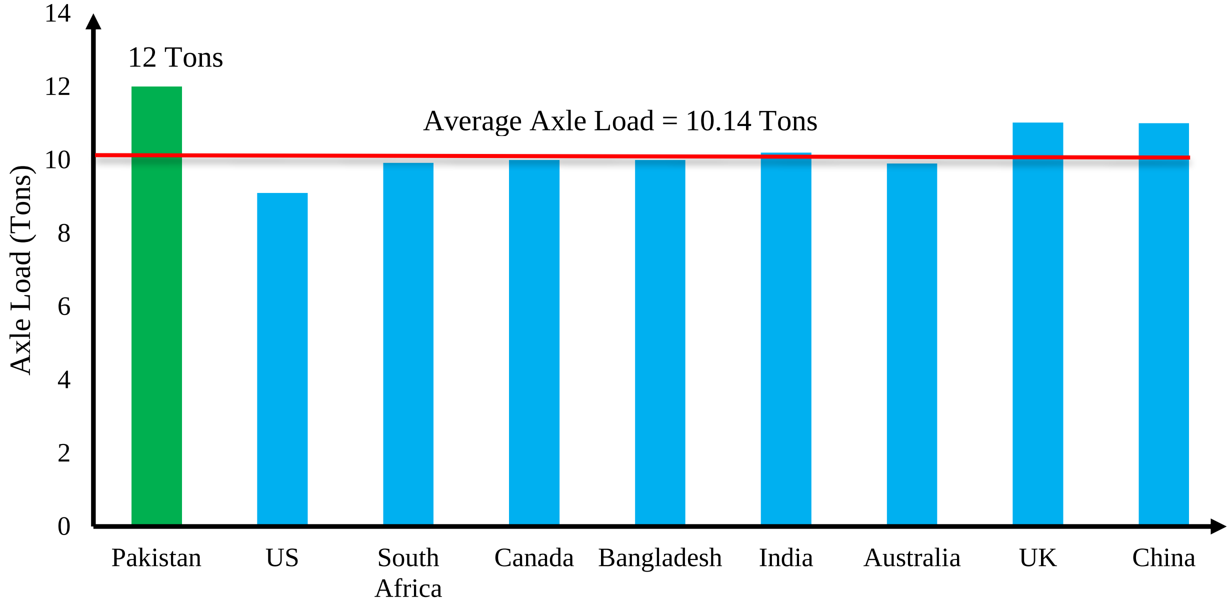


Figure.3.2 Single Axle Load Comparison

The tandem axle load comparison of selected countries presented in Figure 3.3 revealed that load limits of three countries exceed the average axle load limit. It was also revealed that axle load limit of Pakistan is higher than the average tandem axle load of 18.27 tons.

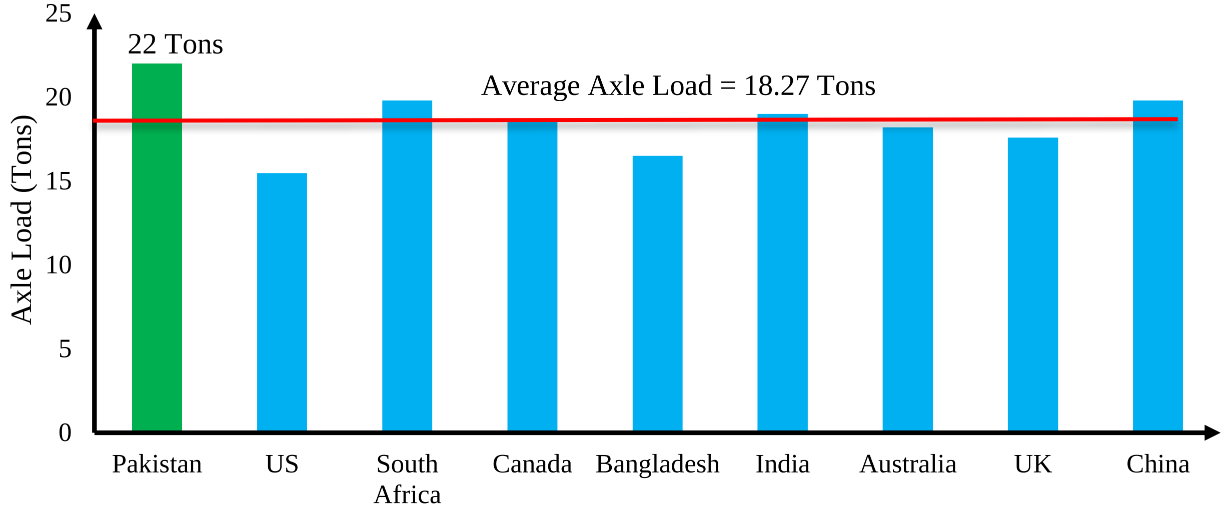


Figure 3.3 Tandem Axle Load Comparison

The tridem axle load comparison of selected countries presented in Figure 3.4 revealed that load limits of four countries exceed the average axle load limit. It was also revealed that axle load limit of Pakistan is higher than the average tridem axle load of 23.94 tons.

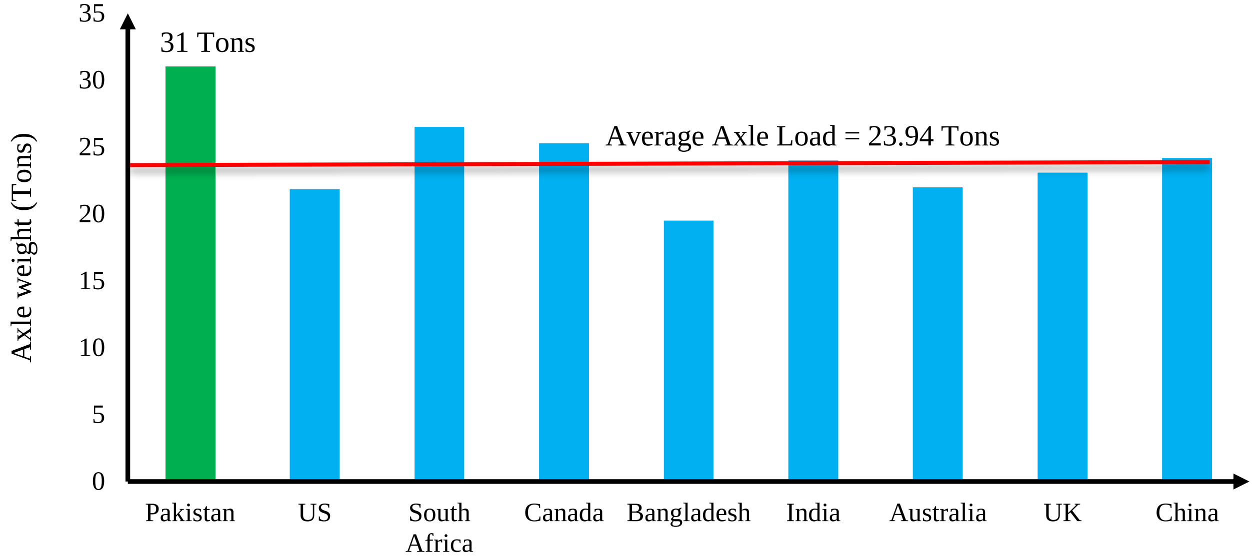


Figure 3.4 Tridem Axle Load Comparison

The ESALs were calculated for steering, single, tandem and tridum axles using AASHTO 4th power law (Equation 3.1)

$$ESAL = \left[\frac{Axle\ Load}{Standard\ Axle\ Load}\right]^4 \tag{3.1}$$

The ESAL values for steering, single, tandem and tridem axles are presented in the Table 3.9. The standard axle load of 18,000 pounds (8.19 tons), 34,000 pounds (15.47 tons) and 48,000 pounds (21.84 tons) were used for the calculation of ESALs.

Table 3.9 Comparison of ESALs of Pakistan with Selected Countries

ESALs				
Country	Steering Axle	Single Axle	Tandem Axle	Tridem Axle
Standard	0.67	1.00	1.00	1.00
Pakistan	**0.67**	**4.63**	**4.11**	**4.08**
USA	0.67	1.52	1.00	1.00
South Africa	1.04	2.16	2.69	2.18
Canada	0.97	2.23	2.14	1.81
Bangladesh	0.67	2.23	1.30	0.64
India	0.73	2.42	2.28	1.46
Australia	0.81	2.14	1.92	1.03
UK	1.34	3.29	1.68	1.26
China	0.81	3.27	2.69	1.51

By comparison of national ESALs with selected countries, it was revealed that due to higher individual axle load limits Pakistan axles are very damaging with ESAL values of 4.63, 4.11 and 4.08 for single, tandem and tridem axles respectively.

3.7 Chapter Summary and Conclusion

In this chapter firstly the current truck weight regulations and overloading issues in Pakistan have been reviewed. Then the trend of road and rail freight transport was discussed, which showed an increased dependence on road network for freight transportation. GVW limits for different types of trucks and axle load limits implemented by NHSO were discussed.

The individual axle load limits of selected countries were compared with Pakistan regulations in the last section. It was revealed that Pakistan axle load limits are very high. Accordingly, higher ESAL values have been observed for Pakistan which means that truck axles in Pakistan cause more damage to the pavement structure as compared to other selected countries.

CHAPTER 4. FORMULATION OF MR&R STRATEGIES AND PDC ESTIMATION

4.1 Introduction

In this chapter, MPDC was estimated for NHS of Pakistan. For model estimation, cost data were obtained from the MR&R strategies. Total traffic load (ESALs) were calculated using AADT and WIM data. Statistical model was estimated using OLS regression techniques. Lastly, a comparison is carried out between current road use toll and actual damage incurred by different truck classes to pavement for N-5.

4.2 Data Collection and Collation

For estimation of MPDC the first requirement is the collection of valid data. The data were collected from number of sources, and were compiled in the form of a database. Different past published reports of NTRC and NHA, NHA annual maintenance plans and traffic data from various WIM stations located on national highway network were collected and explored to extract the required information. The details of these data are explained one by one in the ensuing paragraphs.

4.2.1 Weigh In Motion (WIM) Station Data

Data of four WIM stations named Sangjani, Eminabad, Peshawar and Rashakai located on N-5 were collected for the year 2012. The raw data contained the information on truck GVW, truck class, no. of axles, axle weight, date and time, vehicle ID, and axle spacing. The data at each WIM station were sorted into thirteen truck classes including buses and wagons (Table 4.1)

Table 4.1 GVW and Average Axle Weights

Truck Class	GVW (Tons)	Steering Axle (Tons)	Single Axle 1 (Tons)	Single Axle 2 (Tons)	Single Axle 3 (Tons)	Tandem Axle 1 (Tons)	Tandem Axle 2 (Tons)	Tridem Axle (Tons)
3	17.16	5.17	11.99	-	-	-	-	-
4	17.16	5.17	11.99	-	-	-	-	-
5	31.12	7.08	12.13	11.99	-	-	-	-
6	40.98	7.08	-	-	-	33.90	-	-
7	48.22	5.59	-	-	-	-	-	42.63
8	36.95	5.59	12.59	9.25	9.52	-	-	-
9	44.41	5.59	9.52	-	-	29.30	-	-
10	45.52	5.59	12.89	-	-	27.04	-	-
11	49.84	3.99	-	-	-	23.33	22.52	-
12	42.51	3.99	9.62	6.38	-	22.52	-	-
13	42.56	3.99	7.52	7.72	-	23.33	-	-
14	42.56	3.99	9.57	-	-	-	-	32.00
15	79.3	5.61	9.89	-	-	32.42	31.38	-

The data were used to determine the percentage of each truck class present in the truck stream. The total truck count observed was greatest at Sangjani WIM station followed by Eminabad, Rashakai and Peshawar. The proportions calculated for each class of truck at all WIM stations are summarized in the Table 4.2. It can be observed that the truck class three and four has the highest contribution in traffic stream while all other truck classes contribute very low percentages in the truck traffic stream.

Table 4.2 Percentage of Trucks for Different Truck Classes

Truck Class	WIM Station								Average percentage (%)
	Sangjani		Eminabad		Peshawar		Rashakai		
	No of Trucks	(%)	No of Trucks	(%)	No of Trucks	(%)	No of Trucks	(%)	
3	4411	20.01	1382	15.47	436	25.95	783	42.10	25.9
4	4411	20.01	1382	15.47	436	25.95	783	42.10	25.9
5	5116	23.21	1711	19.15	42	2.50	94	5.05	12.5
6	5116	23.21	1711	19.15	42	2.50	94	5.05	12.5
7	652	2.96	439	4.91	166	9.88	25	1.34	4.8
8	652	2.96	439	4.91	166	9.88	25	1.34	4.8
9	652	2.96	439	4.91	166	9.88	25	1.34	4.8
10	652	2.96	439	4.91	166	9.88	25	1.34	4.8
11	35	0.16	100	1.12	7	0.42	-	-	0.4
12	35	0.16	100	1.12	7	0.42	-	-	0.4
13	35	0.16	100	1.12	7	0.42	-	-	0.4
14	35	0.16	100	1.12	7	0.42	-	-	0.4
15	238	1.08	594	6.64	32	1.9	6	0.32	2.4
Total	22040	100	8936	100	1680	100	1860	100	100

4.2.2 Average Annual Daily Traffic (AADT)

AADT data were obtained from NHA Annual Maintenance plan for the year 2012-13 (NHA, 2013). NHA has divided National highway network into total of 709 sections. The data extracted for each section were comprised of AADT, length of the segment in kilometers, surface type and road class.

AADT data were sorted into six traffic groups: (1) very high traffic, (2) high traffic, (3) medium traffic, (4) medium to light traffic, (5) light traffic and (6) very light traffic. The details of six traffic groups are provided in Table 4.3.

Table 4.3 Grouping of Pavements Based on AADT

Traffic Group	AADT Range	Number of Road Segments	Average AADT
Very High Traffic	AADT>25,000	25	40,956
High Traffic	18,000< AADT <25,000	29	21,625
Medium Traffic	12,000 <AADT <18,000	97	15,166
Medium to Light Traffic	8,000<AADT <12,000	146	10,717
Light Traffic	4,000< AADT <8,000	313	6,995
Very Light Traffic	AADT<4000	99	3,730

4.2.3 Treatment Costs

NHA uses different types of rehabilitation and maintenance treatments for its highway system. The notables are: functional overlay 30 mm thick, 50 mm thick, functional overlay 50 mm thick with deep patching and cold milling, structural overlay 100 and 120 mm thick, structural overlay 120 mm thick with deep patching, thin surface treatment, crack sealing and patching.

The treatment costs for commonly used treatments obtained from NHA in 2013 constant rupees per lane-kilometer (12 feet wide lane) are presented in Table 4.4. Further details of table of treatment costs are provided in appendix A.

Table 4.4 Rehabilitation and Maintenance Treatment Costs

Ser.	Treatment Type	Treatment Cost (Million per Lane-km)
1	Functional Overlay 30 mm thick	3.46
2	Functional Overlay 50 mm thick	4.95
3	Functional Overlay 50 mm thick (with Deep Patching)	5.05
4	Functional Overlay 50 mm thick (with Cold Milling)	6.28
5	Structural Overlay 100 mm thick	8.82
6	Structural Overlay 120 mm thick	10.27
7	Structural Overlay 120 mm thick (with Deep Patching)	10.42
8	Existing Surface Treatment with/TST	3.3
9	Reconstruction 25 cm WBM Base / 13 cm AC	17.09
10	Reconstruction 25 cm WBM Base / 16 cm AC	19.13
11	Reconstruction 25 cm WBM Base / 5 cm AC	9.66
12	Reconstruction 25 cm Aggregate Base / 13 cm AC	15.71
13	Reconstruction 30 cm Aggregate Base / 13 cm AC	16.08
14	Reconstruction 20 cm WBM / TST	9.23
15	Reconstruction 20 cm WBM / DST	8.98
16	Patching	1.7
17	Crack Sealing	1.7

(NHA, 2013)

4.2.4 Treatment Service Lives

Reliable estimates of treatment service lives of commonly used treatments are not available from NHA. Treatment service life is an important input for MR&R strategy formulation. Questionnaire survey technique was used to get experts opinion on service lives of commonly used treatments. The nature of the recent work was highlighted in the questionnaire and opinion on minimum, maximum and average service life of the commonly used treatments by NHA was asked. The opinions given by the experts were observed critically and the averages of service lives were used in the study. The minimum, maximum and average service lives of treatments used in the study obtained through experts' opinion are summarized in the Table 4.5.

Table 4.5 Treatment Service Life of Commonly Used Treatments by NHA

Sr.	Treatment Type	Service Life (Years)		
		Minimum	Maximum	Average
1.	Functional Overlay 30 mm thick	3	7	4
2.	Functional Overlay 50 mm thick	3	7	5
3.	Functional Overlay 50 mm thick (Deep Patching)	4	7	6
4.	Functional Overlay 50 mm thick (Cold Milling)	5	7	6
5.	Structural Overlay 100 mm thick	4	7	6
6.	Structural Overlay 120 mm thick	4	8	6
7.	Structural Overlay 120 mm thick (Deep Patching)	6	10	8
8.	Existing Surface Treatment/TST	1	3	2.5
9.	Structural Overlay 12 cm thick	6	10	8

4.2.5 ESAL Calculation for Truck Classes using WIM Data

The ESALs were calculated for each truck class using the average axle weights (Table 4.1). The ESALs were calculated for each of the axle for a specific truck class using AASHTO'S fourth power law as follows.

$$ESAL = \left[\frac{Axle\ Load}{Standard\ Axle\ Load}\right]^4 \quad (4.1)$$

The standard axle load of 18,000 pounds (8.19 tons), 34,000 pounds (15.47 tons) and 48,000 pounds (21.84 tons) were used for the estimation of ESALs. The average ESALs calculated for different truck configuration are presented in the Table 4.6.

Table 4.6 ESALs for Different Truck Classes

Truck Class	Axle Type						Average Truck ESAL
	Steering	Single-1	Single-2	Single-3	Tandem-1	Tandem-2	Tridem	
3	0.159	4.612	-	-	-	-	-	4.771
4	0.159	4.612	-	-	-	-	-	4.771
5	0.561	4.831	4.612	-	-	-	-	10.004
6	0.561	-	-	-	23.151	-	-	23.712
7	0.218	-	-	-	-	-	14.574	29.366
8	0.218	5.607	1.634	1.833	-	-	-	9.291
9	0.218	1.833	-	-	12.919	-	-	14.970
10	0.218	6.160	-	-	9.371	-	-	15.750
11	0.057	-	-	-	5.193	4.509	-	5.250
12	0.057	1.911	0.370	-	4.509	-	-	6.846
13	0.057	0.714	0.793	-	5.193	-	-	6.756
14	0.057	1.872	-	-	-	-	4.627	11.183
15	0.221	21.35	-	-	19.365	16.998	-	21.721

The summation of ESALs calculated for each axle of a truck class gives the average ESAL of that truck class. It can be noticed that truck class three and four are generating lowest ESAL value of 4.771 while truck class six and seven are producing much higher values of ESAL (23.712 and 29.366 respectively). Truck class eleven, twelve and thirteen has lesser no of ESALs whereas truck class fifteen is also producing higher value of ESAL that is 21.721.

4.3 Comparison of ESALs with Past Studies in Pakistan

In the past, various studies were carried out that calculated ESALs for different configurations of trucks in Pakistan. NTRC – 1982, ACE – 1988, RR&MTI – 1989, NESPAK – 1993 and NHA – 1995 are major studies carried out in the past for ESAL estimation. A comparison of ESALs estimated in past studies is provided in Table 4.7.

Table 4.7 Comparison of ESAL Estimates between Past Research Efforts and Present Study

Truck Configuration	NTRC (1982)	ACE (1988)	RR&MTI (1989)	NESPAK (1993)	NHA (1995)	Present Study (2013)
2-Axle Single	3.30	4.96	6.33	7.4	6.49	4.77
3-Axle Single	-	-	-	-	16.62	10.01
3-Axle R.Tandem	-	7.63	24.82	26.72	18.48	23.71
4-Axle Single	-	9.77	9.68	-	19.00	9.291
4-Axle R.Tandem	11.40	18.07	26.46	25.05	17.30	15.75
5-AxleTandem	5.5-9.2	6.95	12.64	28.3	-	5.204
6-Axle T. Tridem	-	9.04	-	22.56	27.96	21.721

The marked difference in ESAL calculated in different past studies may be attributed to quality of data and methodology used for ESAL estimation.

4.4 Formulation of Life Cycle MR&R Profiles

Pavements are constructed to serve for longer periods of time and include all costs incurred during the life cycle besides the initial construction cost. The costs incurred during pavement life cycle include rehabilitation, periodic maintenance, routine maintenance and reconstruction. Consider a general pavement maintenance and rehabilitation (M&R) profile, also termed as "strategy" (Figure 4.2). An M&R profile is a set of maintenance and rehabilitation activities over one life cycle of a pavement segment [Ahmed, 2012]. It is assumed that the pavement profile starts with the reconstruction cost at year zero and followed with different rehabilitation treatments whether functional or structural at specific time intervals while maintenance treatments are applied at each year during "N" years of pavement life.

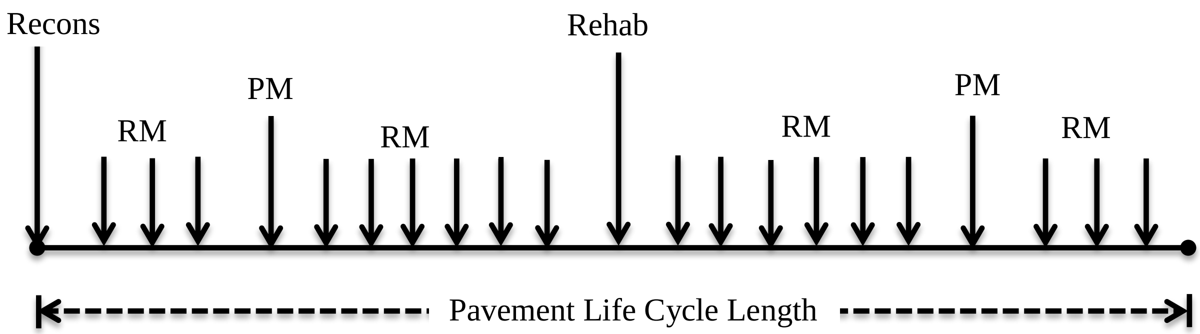


Figure 4.1 Typical Pavement Life Cycle MR&R Profile

M&R profiles were formulated based on the treatments types and their service lives. A total of thirty M&R profiles were formulated for six traffic loading levels on national highways using twenty five years life cycle length. Thus, five M&R profiles were formulated for each level of traffic loading (very high, high, medium, medium to light, light and very light). The time span for each M&R treatment (functional or structural) was selected based on the range of service lives presented in Table 4.5. The life cycle profiles formulated for each of the traffic loading level are presented in the appendix B.

4.5 Cost of MR&R Profiles

The overall cost of each M&R profile over twenty five years life cycle for six traffic loading levels was determined. For estimation of present worth cost a real interest rate of 5% was used. The present worth of M&R treatment was estimated using the interest equation as follows.

$$PW_{M\&R} = \sum_{i=1}^{m1} \times \left[\frac{Cost_i{}^{Rehab}}{(1+r)^{t\_Rehab_i}}\right] + \sum_{i=1}^{m2} \times \left[\frac{Cost_i{}^{PM}}{(1+r)^{t\_PM_i}}\right] + \sum_{i=1}^{m2} \times \left[\frac{Cost^{RM}}{(1+r)^{t\_RM}}\right] \tag{4.2}$$

Where: PW $_{(M\&R)}$ = present worth of rehabilitation and maintenance treatment; r = real discount rate, n = the year of application of rehabilitation or maintenance treatment, m1 = the number of rehabilitation treatments applied to the pavement, m2 = the number of periodic maintenance treatments applied to the pavement, m3 = the number of routine maintenance treatments applied to the pavement, Rehab = rehabilitation treatment, PM = periodic maintenance, RM = routine maintenance

Present Worth of MR&R was calculated by adding the reconstruction cost to PW $_{M\&R}$ cost as follows.

$$MR\&R\ Cost = Reconstruction\ Cost + PW_{M\&R} \tag{4.3}$$

After calculating the PW for thirty MR&R profiles, EUAC was determined using the equation as follows.

$$EUAC_{(MR\&R\ Cost)} = \left[MR\&R\ Cost \times \left(\frac{i(1+i)^n}{(1+i)^n - 1}\right)\right] \tag{4.4}$$

4.6 Estimation of ESAL for MR&R Profiles

The average annual numbers of ESALs experienced by the pavement during twenty five years of life cycle were determined using GVWs and traffic data discussed in section 4.2.

The ESAL estimation involved the sum of annual ESALs for each truck class in each traffic group as follows.

$$\sum_i^k ESAL = Truck\ AADT \times 365 \times D_d \times L_d \times G_f \times \%Class_i \times ESAL\ Class_i \quad (4.5)$$

Where;
ESAL = Sum of Equivalent Single Axle Load of all truck classes for each traffic group
AADT = Average Annual Daily Truck Traffic
D_d = Directional distribution factor
L_d = Lane distribution factor
G_f = Growth factor
%Class = Percentage of trucks in Class i
ESAL $Class_i$ = Individual ESAL of trucks in Class i

ESALs were determined assuming that traffic stream composed of 25% trucks. Directional distribution was taken as 0.5 considering that 50% truck traffic will be in one direction and other 50% will be in opposite direction. Lane distribution factor was considered as 0.8 assuming that 80% trucks will be travelling in the outer lane. Growth factor was calculated as follows.

$$G_f = \left[\frac{(1+i)^n - 1}{i \times Y}\right] \quad (4.6)$$

Where; r = Real discount rate, n = number of years for which growth factor has to be applied, Y = Number of years

4.7 Model Development for Pavement Damage Cost Estimation

MR&R profiles formulated for each traffic group helped to generate thirty observations for model estimation. For the model estimation EUAC was considered as response variable (Y) and average annual ESALs as explanatory variable (X). Ordinary Least Square (OLS) Regression techniques were used for the estimation of model. Different functional forms for the model were tried and the transformations to the response variable "Y" was also done to improve the model fit and correct the model assumptions like constant error variance. The different functional forms that were tried included: natural log, square root, square, reciprocal, power, inverse square and inverse square root. The estimated results for all these functional forms were analyzed critically. The model with square root of EUAC was found to be best with R-square value of 0.77 and final functional form of the model is as follows.

$$\sqrt{EUAC} = \beta_\circ + \beta_1 \times (ESALs) \tag{4.7}$$

Where; β_0, β_1 = Model Coefficients, $\sqrt{EUAC}$ = Square root of equivalent uniform annual cost per lane Km, ESALs = average annual number of equivalent single axle load per lane Km
The model details are summarized in Table 4.11.

Table 4.8 Model Estimates for MPDC Estimation

Variable	Coefficient	t-Value	P-Value
Intercept	1457.157	145.054	<0.0001
ESALs	0.000147	9.686	<0.0001
R- Square	0.77		
Number of observations	30		
Mean Absolute Percentage Error	0.02		

The model results suggest that MR&R cost depends on traffic loading (ESALs). The model estimates are intuitive. The model results suggest that ESALs are positively associated with EUAC. The model suggests that the pavement repair costs will be higher when the pavement will sustain high traffic loading (higher annual average ESALs).

The model accuracy is evaluated by estimating mean absolute percentage error (MAPE) value as follows.

$$MAPE = \frac{1}{n}\sum_{i=1}^{n}|PE_i| \tag{4.8}$$

Where, PE $_i$ = (A_i – P_i) / A_i is the percentage error for observation i of the actual and predicted rate. The MAPE value for the estimated model is 0.02. The MAPE value closer to zero depicts higher prediction accuracy of the model.

4.8 Marginal Pavement Damage Cost Estimation

MPDC is the increase in agency's MR&R total expenditure due to one additional vehicle load on given pavement segment. MPDC was estimated by differentiating the estimated pavement damage cost function (equation 4.7) with respect to the ESALs as follows.

$$\sqrt{EUAC} = \beta_\circ + \beta_1 \times (ESALs) \tag{4.9}$$

$$EUAC = \left[\beta_{\circ} + \beta_1 \times (ESALs)\right]^2 \tag{4.10}$$

$$\frac{d(EUAC)}{d(ESAL)} = \frac{d}{d(ESAL)} \left[\left[\beta_{\circ} + \beta_1 \times (ESALs)\right]^2\right] \tag{4.11}$$

$$\frac{d(EUAC)}{d(ESAL)} = 2\left[\beta_{\circ} + \beta_1 \times (ESALs)\right] \left[\frac{d}{d(ESAL)}(\beta_{\circ}) + \frac{d}{d(ESAL)}(\beta_1 \times ESALs)\right] \tag{4.12}$$

$$\frac{d(EUAC)}{d(ESAL)} = 2\left[\beta_{\circ} + \beta_1 \times (ESALs)\right] [0 + \beta_1] \tag{4.13}$$

$$\frac{d(EUAC)}{d(ESAL)} = 2(\beta_1)\left[\beta_{\circ} + \beta_1 \times (ESALs)\right] \tag{4.14}$$

So,

$$\text{MPDC} = 2(\beta_1)\left[\beta_{\circ} + \beta_1 \times (ESALs)\right] \tag{4.15}$$

Where, MPDC = Marginal pavement damage cost (Rs. per ESAL km), ESAL = Average annual number of equivalent single axle load

Estimated cost function presented in equation 4.7 can be used to obtain the MPDC for different traffic levels. Using the estimated cost function and annual average ESALs marginal pavement damage cost was calculated for national highway system. The estimated MPDC for the year 2013 was 0.451 per ESAL-Km (2013 Constant Rs). MPDC for 2014 was estimated as Rs. 0.494 per ESAL-Km (2014 constant Rs) using the inflation factor of 1.0959 (CPI 2013 = 172.45 and CPI 2014 = 189) for Pakistan.

The pavement deterioration (the loss of pavement performance) is attributed to two factors: loading and climate [Ahmed et al, 2014]. Considering 80 – 20% split for load and non-load share of PDC, MPDC due to loading was estimated as Rs. 0.395/ESAL-Km (2014 constant Rs).

4.9 Comparison between Current Toll Rate and Actual Pavement Damage Cost

A comparison of road use fee based on MPDC with existing road use fee (toll rate) was carried out. For comparison purpose 275 km road segment of N-5 from Lahore to Islamabad was considered. Currently there are six toll plazas on this N-5 segment and two/three axle trucks pay Rs 110 at each toll plaza while trucks exceeding more than three axle pay Rs 210 at each toll plaza [NHA, 2014]. Location of toll plazas on N-5 between Islamabad and Lahore is shown in Figure 4.4 as follows.

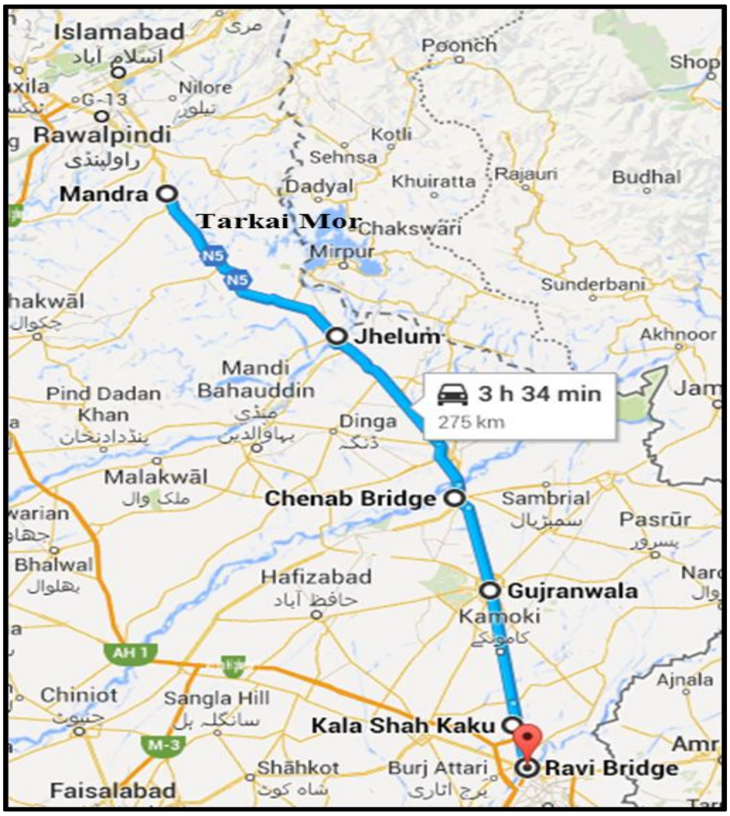


Figure 4.2 Location of Toll Plazas on N-5 b/w Islamabad and Lahore

The current road use fee of six toll plazas and road use fee based on MPDC for two, three, four and five and more than five axle trucks are calculated as follows.

a. <u>Case 1: Two Axle Truck</u>

Currently two axle trucks are charged Rs. 110 at each toll plaza and there are total of six toll plazas between Lahore to Islamabad on N-5. So, the current road user charges (flat fee) for two axle trucks are Rs. 660. The charges based on MPDC (calculated using the equation 4.16) are.

$$\text{Actual PDC} = Distance \times ESAL \times MPDC \qquad (4.16)$$

A distance of 275 km, average ESAL value of 4.77 and MPDC value of 0.395/ESAL-Km (2014 constant Rs) were used in the equation for the calculation of actual PDC. The charges based on actual PDC for two axle truck class were estimated as Rs. 518.

b. Case 2: Three Axle Truck

Currently three axle trucks are charged Rs. 110 at each toll plaza and there are total of six toll plazas between Lahore to Islamabad on N-5. So, the current road user charges (flat fee) for two axle trucks are Rs. 660. The charges based on MPDC were calculated using the equation 4.9. A distance of 275 km, average ESAL value of 16.86 and MPDC value of 0.395/ESAL-Km (2014 constant Rs) were used in the equation for the calculation of actual PDC. The charges based on actual PDC for three axle truck were estimated as Rs. 1831.

c. Case 3: Four Axle Truck

Currently four axle trucks are charged Rs. 220 at each toll plaza and there are total of six toll plazas between Lahore to Islamabad on N-5. So, the current road user charges (flat fee) for two axle trucks are Rs. 1320. The charges based on MPDC were calculated using the equation 4.9. A distance of 275 km, average ESAL value of 17.34 and MPDC value of 0.395/ESAL-Km (2014 constant Rs) were used in the equation for the calculation of actual PDC. The charges based on actual PDC for three axle truck class were estimated as Rs. 1884.

d. Case 3: Five and More than Five Axle Truck

Currently five and more than five axle trucks are charged Rs. 220 at each toll plaza and there are total of six toll plazas between Lahore to Islamabad on N-5. So, the current road user charges (flat fee) for two axle trucks are Rs. 1320. The charges based on MPDC were calculated using the equation 4.9. A distance of 275 km, average ESAL value of 13.64 and MPDC value of 0.395/ESAL-Km (2014 constant Rs) were used in the equation for the calculation of actual PDC. The charges based on actual PDC for three axle truck class were estimated as Rs. 1478.

The comparison between current toll rate and road use fee based on MPDC for two, three, four and five and more than five axle trucks is presented in Table 4.12.

Table 4.9 Comparison between Current Toll Rate and Road Use Fee Based on MPDC

Truck Class	Current Toll Rate (Rs – 2014)	Road Use Charges based on MPDC (Rs – 2014)	Over/Under Payment of Road Use Fee
Two Axle	660	518	+21.50%
Three Axle	660	1831	-177.4%
Four Axle	1320	1884	-42.735
Five & More Axle	1320	1478	-11.96%

The comparison Table shows that the current road use fee (toll rate) to charge commercial vehicles is inequitable as it fails to charge road use fee based on the damage incurred by each class of vehicle. The damage (ESALs) caused by two axle trucks is minimum among other truck classes therefore, its current road use fee may be reduced. The truck classes with five and more than five axles have lesser damage (ESALs) than three and four axle trucks so, these truck classes may have reduced current toll rate. So it can be summarized that two axle truck class is overpaying the current road use fee while truck classes with three, four and five and more than five axles are underpaying the current use fee. The distribution of road use fee based on the damage incurred by each class of vehicle will encourage the use of trucks with more number of axles thus reducing the overall pavement damage.

4.10 Chapter Summary and Conclusion

In this chapter, the pavement damage estimation cost model for Pakistan was estimated and model results were discussed. The data for model estimation were obtained from NHA. Marginal pavement damage cost was also calculated using the estimated model.

For the model estimation, EUAC was used as response variable and ESAL was used as explanatory variable. The MPDC was estimated as Rs. 0.395 (2014 constant Rs) per ESAL-Km assuming 80% load share damage. The analysis of the results indicated that with the increase of ESALs, there is an increase in the pavement life cycle costs (maintenance, rehabilitation and reconstruction). Lastly, the comparison of current road use fee and actual damage cost was carried out and it was concluded that current road use fee (toll rate on N-5) to charge the commercial vehicles is inequitable.

CHAPTER 5. SENSITIVITY ANALYSIS

5.1 Introduction

In this chapter the sensitive analysis was carried out to examine the effect on MPDC estimates by the variation in different variables. The variables that were investigated included: pavement life cycle length, interest rate, and rehabilitation and reconstruction costs.

5.2 Effect of Variation in Pavement Life Cycle Length on MPDC Estimates

In this study, MPDC estimation was carried out for twenty five year life cycle length as recommended by the pavement experts. The life cycle length was varied from fifteen to thirty years and the effect on MPDC was examined. In recent years, agencies are trying to move towards longer pavement life cycle lengths, in order to reduce repair expenditures and more frequent maintenance and rehabilitation treatments. The methodology adopted to examine the impact of variation in pavement life cycle length on MPDC is discussed as follows:

- In the first step, MR&R profiles were formulated for 15, 18, 21, 27 and 30 year’s life cycles.
- From the formulated profiles, annual average ESALs and EUAC for each profile for five life cycle lengths were estimated.
- Models were developed from the estimated data for each of the five life cycle length separately.
- MPDC was estimated using the developed models for five selected life cycle lengths in the final step.

The model results and MPDC estimates are presented in Tables 5.1 and 5.2 as follows.

Table 5.1 Model Estimates Using Different Life Cycle Lengths

Life Cycle length (Years)	Variable	Coefficient	t- value	R^2	N
15	Constant	1489.132	103.263	0.827	30
	ESAL	0.000252	11.586		
18	Constant	1466.696	109.501	0.836	30
	ESAL	0.000242	11.979		
21	Constant	1475.756	108.613	0.743	30
	ESAL	0.000184	8.988		
25 (Base Case)	Constant	1457.147	145.054	0.770	30
	ESAL	0.000147	9.686		
27	Constant	1460.082	218.757	0.859	30
	ESAL	0.000132	13.073		
30	Constant	1463.193	237.105	0.852	30
	ESAL	0.000119	12.725		

Table 5.2 MPDC Estimates Using Different Life Cycle Lengths

Life Cycle length (Years)	MPDC (Rs./ESAL-Km) – 2014 Constant Rs
25 (Base Case)	0.494
15	0.896
18	0.846
21	0.635
27	0.443
30	0.398

The pavement life cycle length has a significant impact on MPDC estimates as shown in Figure 5.1. The minimum value of MPDC is for thirty years life cycle length and maximum value is for fifteen years pavement life cycle length. It can be observed that with the increasing length of pavement life cycle, MPDC estimates are decreasing. The MPDC values are small for longer pavement lengths. Thus, the highway agencies should select the appropriate pavement life cycle length for MPDC estimation.

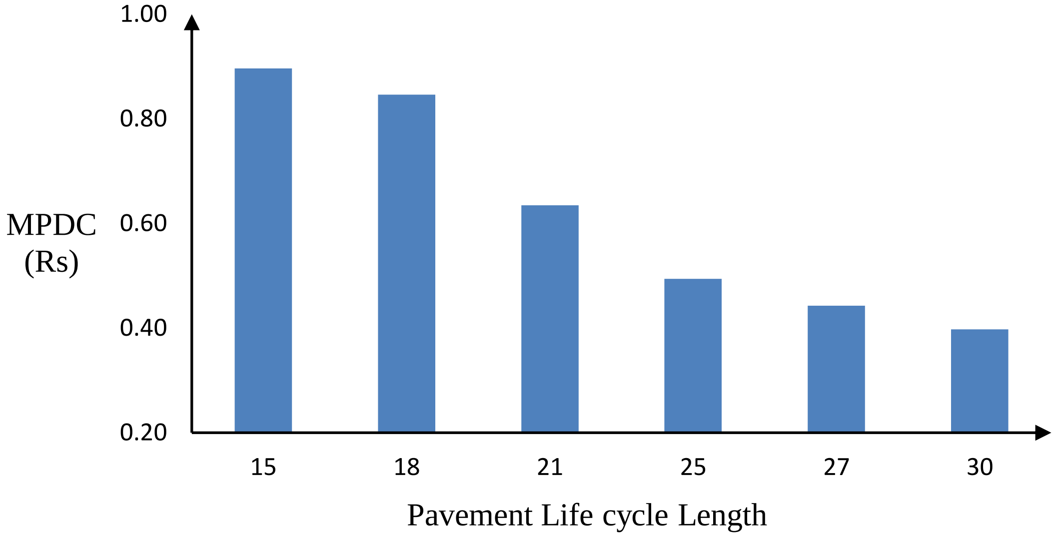


Figure 5.1 Variation in MPDC with Change in Pavement Life Cycle Length

5.3 Effect of Variation in Interest Rate on MPDC Estimates

Interest rate can be an important factor in the estimation of MPDC. Different interest rates can result into different EUAC values in each MR&R profile and ultimately will give different MPDC estimates. In this study, a real interest rate of 5% was used. The methodology adopted for MPDC estimation using different interest rates is as follows.

- In the first step, MR&R profiles were formulated for interest rates varying between 2 – 10%. There were nine different cases and 270 MR&R profiles were formulated.
- From the formulated profiles, annual average ESALs and EUAC for 270 profiles were estimated.
- Models were developed from the estimated data for the different interest rate value separately.
- Models were differentiated to obtain MPDC in the final step.

The estimated models and MPDC estimates are presented in Table 5.3 and 5.4 as follows.

Table 5.3 Model Estimates using Different Interest Rates

Interest Rate	Variable	Coefficient	t- value	R^2	N
2%	Constant	1379.885	152.455	0.772	30
	ESAL	0.000133	9.738		
3%	Constant	1399.643	112.446	0.686	30
	ESAL	0.000147	7.813		
4%	Constant	1425.279	138.747	0.764	30
	ESAL	0.000148	9.520		
5% (Base Case)	Constant	1457.157	145.054	0.770	30
	ESAL	0.000147	9.686		
6%	Constant	1500.495	130.775	0.717	30
	ESAL	0.000146	8.4205		
7%	Constant	1519.334	108.253	0.663	30
	ESAL	0.000157	7.4296		
8%	Constant	1541.616	131.785	0.749	30
	ESAL	0.000162	9.1523		
9%	Constant	1569.872	111.363	0.712	30
	ESAL	0.000177	8.3162		
10%	Constant	1596.674	125.478	0.744	30
	ESAL	0.000173	9.025		

Table 5.4 MPDC Estimates for Different Interest Rates

Interest Rate	MPDC (Rs./ESAL-Km) – 2014 Constant Rs
5% (Base Case)	0.494
2%	0.422
3%	0.476
4%	0.488
6%	0.505
7%	0.551
8%	0.578
9%	0.636
10%	0.647

The Figure 5.2 suggests that interest rate variation has significant effect on MPDC estimates. MPDC estimates increase with the increase in interest rate. The real interest rate of 5% is used in this study as base case. Using a different interest rate form the base case can have significant impacts on MPDC estimates.

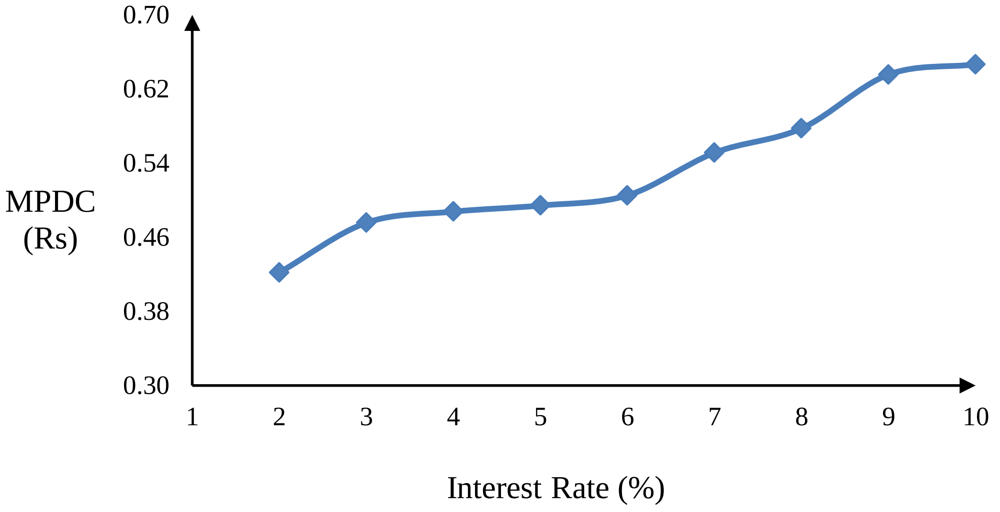


Figure 5.2 Variation in MPDC with Change in Interest Rate

5.4 Sensitive Analysis of MPDC With Respect to Rehabilitation Cost

Reconstruction, rehabilitation and maintenance are the important activities performed during life cycle of pavement. Rehabilitation activities can have significant impacts on MPDC estimates as these activities are performed more costly than other activities. In order to study the impact of variation in rehabilitation costs on MPDC, MR&R profiles were formulated by varying the rehabilitation cost from base case. The MR&R profiles were formulated for ten different cases of rehabilitation cost. The variation of 2%, 4%, 6%, 8% and 10% in rehabilitation costs from the base case was tested. From the formulated profiles, traffic and cost data (ESALs and EUAC) were estimated. The estimated data were then used for development of separate models for ten different rehabilitation cases. MPDC was estimated from the developed models in 2014 constant Rs. The MPDC estimates for different rehabilitation cost scenarios are presented in Tables 5.5.

Table 5.5 MPDC Estimates for Different Rehabilitation Costs Scenarios

Interest Rate	MPDC (Rs./ESAL-Km) (2014 Constant Rs)	%Difference from Base Case
Base Case	0.494	-
+2%	0.500	+1.1%
+4%	0.505	+2.1%
+6%	0.510	+3.1%
+8%	0.518	+4.9%
+10%	0.520	+5.2%
-2%	0.486	-1.7%
-4%	0.481	-2.7%
-6%	0.476	-3.7%
-8%	0.471	-4.6%
-10%	0.454	-8.2%

It was revealed (Figure 5.3) that change in MPDC with changes in rehabilitation cost is linear. Slight variations in rehabilitation cost result into significant variations in MPDC estimates like 10% variation in rehabilitation cost cause 5 - 8% error in MPDC estimation.

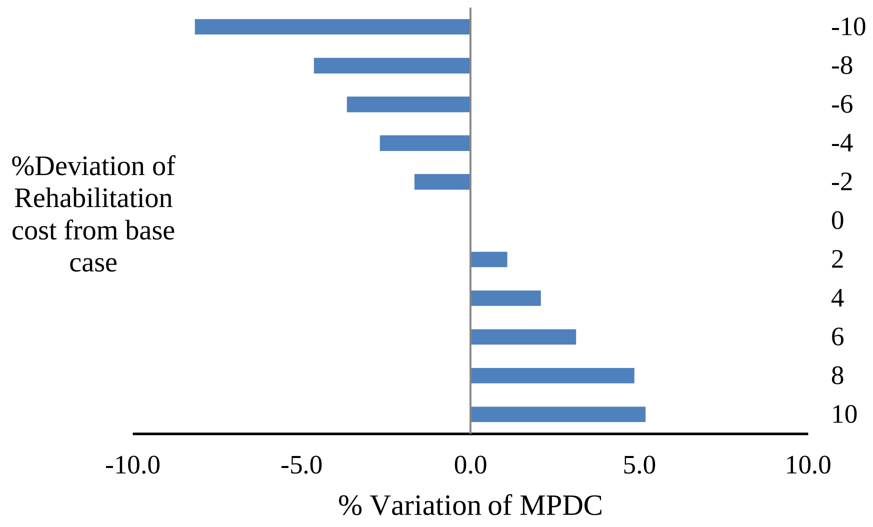


Figure 5.3 Percentage Variation in MPDC with Change in Rehabilitation Cost

5.5 Sensitive Analysis of MPDC With Respect to Reconstruction Cost

In order to analyze the effect of variation in reconstruction costs on MPDC, MR&R profiles were formulated using different cases of reconstruction cost. The MR&R profiles were formulated for ten different cases of reconstruction cost. The variation of 2%, 4%, 6%, 8% and 10% in reconstruction costs from the base case was tested. From the formulated profiles, traffic and cost data (ESALs and EUAC) were estimated. The estimated data were then used for development of separate models for ten different cases. MPDC was estimated from the developed models in 2014 constant Rs. The MPDC estimates for different reconstruction cost scenarios are presented in Tables 5.6.

Table 5.6 MPDC Estimates for Variation in Reconstruction Costs

Interest Rate	MPDC (Rs./ESAL-Km) (2014 Constant Rs)	%Difference from Base Case
Base Case	0.494	-
+2%	0.495	+0.1%
+4%	0.495	+0.1%
+6%	0.504	+2.0%
+8%	0.510	+3.1%
+10%	0.518	+4.9%
-2%	0.486	-1.7%
-4%	0.480	-2.8%
-6%	0.475	-3.9%
-8%	0.469	-5.0%
-10%	0.468	-5.4%

It was revealed that inaccurate estimation of reconstruction cost can vary significantly the MPDC estimates; however the results are not that alarming.

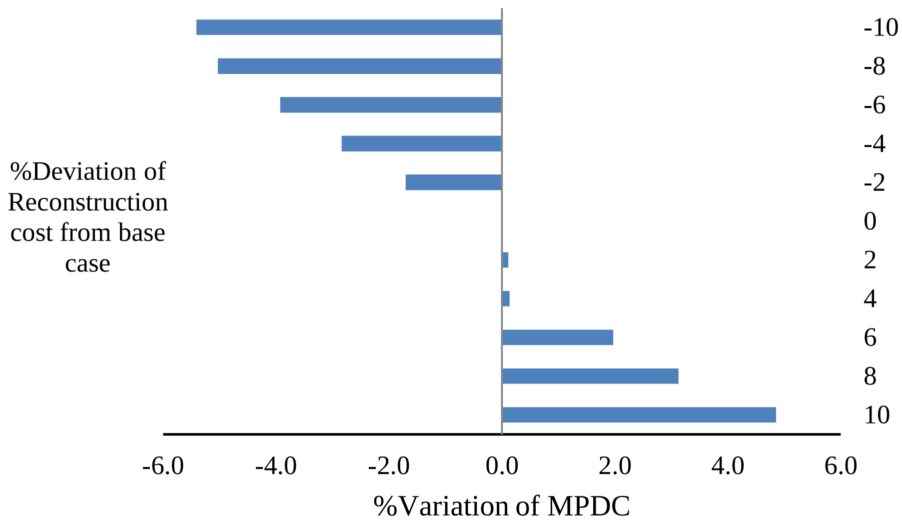


Figure 5.4 Percentage Variation in MPDC with Change in Reconstruction Cost

5.6 Chapter Summary and Conclusions

The sensitivity analysis of MPDC based on the variations in different variables was carried out in this chapter. The analysis revealed that pavement life cycle length, interest rate, and reconstruction and rehabilitation cost can significantly influence the MPDC estimates. Therefore, it is necessary that appropriate pavement life cycle length, interest rate and reliable estimates of rehabilitation and reconstruction cost are used for MPDC estimation.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

6.1 Synopsis of the Research

This research study addressed the emerging issue of pavement damage cost estimation due to commercial truck traffic in Pakistan. The study started with an extensive review of literature on pavement damage cost estimation, both at international and national level. Review of the international studies helped to identify the methodologies and procedures adopted in different countries for estimation of pavement damage cost. The detailed literature review also highlighted the data requirements to carry out the study. Likewise, past available national studies were also reviewed. The literature review helped to narrow down the scope of the study and identify the related issues of adopting study methodology and data availability. Before the estimation of pavement damage cost models, a comprehensive review on current situation of road damage due to heavy vehicles in Pakistan was carried out. The truck configurations and existing truck weight limits enforced in Pakistan were also investigated. The overloading issues and road infrastructure damage due to overloading of trucks were also debated. The weight regulations of heavy vehicles and axle weight limits for selected countries were studied and conversed. A detailed comparison of truck axle weight limits and ESALs for Pakistan with selected countries was carried out and the trends were also discussed.

Finally, present research estimated MPDC for Pakistan. Pavement damage cost model was estimated using MR&R cost and traffic data for national highway system of Pakistan. The actual damage cost incurred by different truck classes was also compared with current toll rate. The effect of different variables e.g. pavement life cycle length, interest rate, rehabilitation and reconstruction cost on MPDC estimates was also observed.

6.2 Research Findings

A thorough review of the past international studies focused on pavement damage cost estimation revealed that there has been lack of serious research efforts to estimate pavement damage cost for Pakistan as no such study has been carried out in the past. A comprehensive and detailed study of the current truck weight regulations and enforcements in Pakistan revealed that country has experienced a moderate increase in road infrastructure but at the same time highways share a major burden of commercial traffic as compared to railways. Past research has shown that increased overloading of trucks and absence of strict enforcement of laws and regulations have led to severe damage to pavements in Pakistan and ultimately the need of frequent rehabilitation and maintenance treatments has increased. Further, comparison of truck axle weights regulations in Pakistan with selected countries revealed that Pakistan has higher truck axle load limits. Higher individual axle load limits are resulting into faster pavement deterioration in Pakistan.

As part of this study OLS regression model was developed using cost and traffic data from NHA. Model results revealed that MR&R costs are significantly positively associated with average annual ESALs. It was observed that increase in average annual ESALs result in higher pavement maintenance cost. Marginal PDC for national highway system (NHS) was estimated to be Rs. 0.494/ESAL-km (2014 constant Rs) for the year 2014. Load share of MPDC was estimated as Rs. 0.395/ESAL-Km (2014 constant Rs) (80% load share in pavement damage cost). The comparison of current toll and actual damage cost revealed that it is appropriate to charge vehicles based on MPDC and toll rate on national highway system shall be based on damage (ESALs) caused by each vehicle class.

Finally, the sensitivity analysis of MPDC based on the variations in different variables was carried out in this chapter. The analysis revealed that pavement life cycle length, interest rate, reconstruction and rehabilitation costs can significantly influence the MPDC estimates. Therefore, it is necessary that appropriate pavement life cycle length, interest rate and reliable estimates of rehabilitation and reconstruction costs are used for MPDC estimation.

6.3 Recommendations and Direction for Future Research

Comprehensive and thorough research is essential to identify the factors responsible for high pavement damage cost and to find the counter measures for controlling the overloading and reducing the high pavement repair cost in Pakistan. The present study is based on limited data set therefore, it is also recommended to carry out a comprehensive study at national level for pavement damage cost estimation. Also, future research effort should be directed to explore the effects of other variables like pavement age, pavement type and climate on pavement damage cost.

LIST OF REFERENCES

Associated Consulting Engineers (ACE) Transportation Engineering Services, (2001). "Final Report on Traffic Study, Axle Load Survey and Pavement Design including supplement and addendum ".

Ahmed, A., Bai, Q., Lavrenz, S., Labi, S., (2014). "Estimating the Marginal Cost of Pavement Damage by Highway Users on the Basis of Practical Schedules for Pavement Maintenance, Rehabilitation and Reconstruction, structure and Infrastructure Engineering: Maintenance, Management, Life Cycle Design and Performance". DOI: 10.1080/15732479.2014.935950

Blower, D., Woodrooffe, J., (2011). "Survey of the status of truck safety: Brazil, China, Australia and the United States." UMTRI.

Bosman, J., (2006). "Traffic loading characteristics of South African heavy vehicles." 8th International Symposium on heavy vehicle weights and dimensions, ISBN Number: 1-920-01730-5 .

Berthelot, C., Taylor, B., Bergan, A., and Lindgren, N., (2000). "The importance of commercial vehicle weight enforcement in safety and road asset management." Traffic Technology International, Annual Review pp 234-237.

Berthelot, C., Podborochynski, D., Anthony, A., Marjerison, B., Litzenberger, R., and Kealy, T., (2011). "Quantifying incremental pavement damage caused by overweight trucks." Annual Conference of Transportation Association of Canada.

Chaudry, R., and Memon, A.B., (2013). "Effects of variation in Truck factor on pavement performance in Pakistan." Mehran University Research Journal of Engineering and Technology, volume No. 32 No. 1, ISSN: 0254-7821.

Council for Scientific and Industrial Research (CSIR) Department of Transport, South Africa., (1997). "The Damaging Effects of Overloaded Heavy Vehicles on Roads" ISBN: 1-86844-285-3, Fourth Edition.

Department for Transport, U.K, (2003). "A simplified guide to Lorry types and Weights."

Dodoo, N., and Thorpe, N., (2004). "A pavement damage based system for charging HGVs for their use of road infrastructure." Transport Policy

Economic Survey of Pakistan (2012), Government of Pakistan.

Federal Highway Administration (FHWA), US Department of Transportation., (1995). "Comprehensive Truck Size and Weight study." Special Report 225, Volume 2.

Federal Highway Administration (FHWA), US Department of Transportation., "WIM data Analysts Manual." Publication No. FHWA-IF- 10-018.

Government of India, Ministry of Road Transport and Highways, (1996). "Specification of maximum gross vehicle weight and maximum safe axle weight. "

Government of People's Republic of Bangladesh, Ministry of Communication, BRTA., (2003).

Ghaeli, R., Hutchinson, B.G., Haas, R., and Gillen, D., (2000). "Pavement and Bridge Cost Allocation Analysis of Ontario Canada Intercity highway network". Transportation Research Record 1732.

Hajek, J.J., Tighe, S.L., and Hutchinson, B.G., (1998). "Allocation of pavement damage due to trucks using a Marginal cost method." TRR 1613, TRB, Washington, D.C.

Hine,J.L and Chilver, A.S., (1991). "Pakistan road freight industry an overview. " Overseas Unit, TRRL Research Report 314, ISSN: 0266-5247.

Japan International Cooperation Agency (JICA), National Transport Research Center (NTRC), Ministry of Communications, Government of Pakistan., (2006). "Pakistan Transport Plan Study in Islamic Republic of Pakistan." 2.

Li, Z., Sinha, K.C and McCarthy, P.S (2002). "A determination of load and non-load shares of highway pavement routine maintenance expenditures." Road and Transport Research, volume 11 No 2.

Li, Z., Sinha, k.C., and McCarthy, P.S (2001). "Methodology to determine load and non-load related shares of highway pavement rehabilitation expenditures." Transportation Research Record 1747, paper No. 01-2839.

Liu, C., Li, Y., and Bai, Y (2009). "Determining Pavement Damage Cost Attributable to Truck Traffic in Southern Kansa." Proceedings of the 2009 Mid-Continent Transportation Research Symposium, Ames, Iowa.

Majeed, A., (1984). "Economic Implications of Vehicle Overloading Final Report." National Transportation Research Center, NTRC-71, 37.

Martin, Tim C., (1984). “Estimating Heavy vehicle Road Wear Cost for Bitumenous Surfaced Arterial Roads.” Journal of Transportation Engineering.

Majeed, A., (1982). “Axle Load Survey Final Report.” National Transportation Research Center, NTRC-65.

Mohamad, D., Sinha, K.C and McCarthy, P.S., (2007). “Relationship between pavement performance and routine maintenance Mixed Logit Approach.” Transportation Research Board, paper No. 971076.

Ministry of Industries, Production and Special Initiatives, (2007). “Trucking Policy for Modernization of Trucking sector of Pakistan under National Trade Corridor Improvement Programme.” Government of Pakistan.

National Highway Authority (NHA), (1995). "Axle load study on national highways Pakistan". Government of Pakistan, Ministry of communication.

National Highway Authority (NHA), (2012). "Annual Maintenance Plan". Road Asset Management System Directorate.

National Highway Authority (NHA), (2013). "Annual Maintenance Plan". Road Asset Management System Directorate.

National Highway Authority (NHA), (2005). "NHA Code". Volume-1.

National Transport Commission, Australia, (2005). “Review of heavy vehicle axle load data.”

National Highway Safety Ordinance (NHSO), (2000). “Allowable Load Limits. ”

Ozbay, K., Bartin, B., Yanmaz-Tuzel, O., and Berechman, J., (2007). “Alternative methods for estimating full marginal costs of highway transportation.” Transportation Resarch part A 41 768 - 786.

Prozzi, J., Murphy, M., Loftus-Otway, L., Banerjee, A., Kim, M.,Wu, H., Prozzi, J.P., Hutchison, R., Harrison, R., Walton, C.M., Weissmann, J., Weissmann, A.,Kopits, E., and Cropper, M., (2012). “Oversize/Overweight Vehicle Permit Fee Study.” Center for Transportation Research,The University of Texas at Austin.

Roberts, F.L., and Djakfar, L., (2000). “Cost of pavement damage due to heavier loads on Louisiana highways.” Transportation Research Board, paper No. 00-0441.

Salama, H.K., Chatti, K., and Lyles, R.W., (2006). “Effects of heavy multi axle trucks on flexible pavement damage using in-service pavement performance data.” Journal of Transportation Engineering ASCE.

Social Indicator of Pakistan (2012), Government of Pakistan.

Timm, D., and Peters K., (2008). “Effects Of Increasing Truck Weight Limit On Highway Infrastructure Damage.”

Timm, D.H., Peters, K.D., and Turochy, R.E., (2008). “Highway Pavement Damage and Cost Due to Routine Permitted Axles.”

Timm, D.H., Bower, J.M., and Turochy, R.E., (2007). “Effect of load spectra on Mechanistic-Empirical flexible pavement design.” Transportation Research Road No. 1947, TRB, Washington, D.C.

Transportation Research Board, (2002). "Regulation of Weights, Lengths and Widths of commercial motor vehicles ". Special Report 267

US Department of Transport, Washington D.C, (1995). “Western US-Canada cross border truck size and weight study.” report No. 5.

Vitaliano, D., F., and Held, J., (1990). “Marginal Cost Road Damage and User Charges.” Quarterly Review of Economics and Business, 30(2)

Wen, H., Peng, J.U., Xu-Hong, LI., and Jie, HE., (2012). “Site survey and analysis of highway trucks overloading status QUO in ANHUI.” Journal of Eastern sia society for Transportaion studies, volume 6.

Zhang, Z., Leidy, J., Kawa, I., and Hudson, W., (2007). “Impact of Changing Traffic Characteristics and Environmental Conditions on Flexible Pavements.” Transportation Research Board, paper No. 00-1218.

APPENDIX

Appendix A Treatment Costs Data for the Year 2013

Ser. No.	Maintenance & Rehabilitation Operations	Financial Cost 7.3 M wide Per Km. (Rs. In Million)	Economical Cost 7.3 M wide Per Km. (Rs. In Million)	Financial Cost Per SM. (Rs)	Economical Cost Per SM (Rs)
1	Functional Overlay 30 mm thick	6.92	5.88	948.16	805.94
2	Functional Overlay 50 mm thick	9.89	8.41	1355.03	1151.78
3	Functional Overlay 50 mm thick (with Deep Patching)	10.09	8.58	1382.36	1175.01
4	Functional Overlay 50 mm thick (with Cold Milling)	12.56	10.68	1721.08	1462.92
5	Hot Recycling unit rate	2.60	2.21	356.16	302.74
6	Structural Overlay 100 mm thick	17.64	14.99	2416.35	2053.90
7	Structural Overlay 120 mm thick	20.54	17.46	2813.43	2391.42
8	Structural Overlay 120 mm thick (with Deep Patching)	20.84	17.71	2854.42	2426.26
9	Reconstruction 25 cm WBM Base / 13 cm AC	34.19	29.06	4683.41	3980.90
10	Reconstruction 25 cm WBM Base / 16 cm AC	38.26	32.52	5241.42	4455.21
11	Reconstruction 25 cm WBM Base / 5 cm Asphaltic WC	19.32	16.42	2646.48	2249.51
12	Reconstruction 25 cm Aggregate Base / 13 cm AC	31.42	26.71	4304.21	3658.58
13	Reconstruction 30 cm Aggregate Base / 13 cm AC	32.15	27.33	4403.75	3743.19
14	Reconstruction 20 cm WBM / TST	18.45	15.68	2527.30	2148.21
15	Reconstruction 20 cm WBM / DST	17.96	15.27	2460.14	2091.12
16	Rigid Pavement	24.88	21.14	3407.62	2896.47
17	Existing Surface Treatment/TST	6.6	5.61	904.18	768.55
18	Functional Overlay 30 mm thick for Dual Carriageway	13.24	11.26	907.00	770.95
19	Functional Overlay 50 mm thick for Dual Carriageway	19.63	16.69	1344.80	1143.08
20	Functional Overlay 50 mm thick for Dual Carriageway (with Deep Patching)	20.09	17.07	1375.87	1169.49
21	Functional Overlay 50 mm thick for Dual Carriageway (with Cold Milling)	25.89	22.00	1773.07	1507.11
22	Structural Overlay 12 cm thick for Dual Carriageway	43.95	37.36	3010.40	2558.84
23	Reconstruction 25 cm WBM Base / 13 cm AC (Dual)	70.01	59.51	4795.74	4076.00
24	Reconstruction 25 cm WBM Base / 16 cm AC (Dual)	79.27	67.38	2849.76	4615.28
25	Reconstruction 25 cm WBM base / 5 cm Asphaltic Wearing Concrete (Dual)	41.61	35.37	4641.92	2422.30
26	Reconstruction 25 cm Aggregate Base / 13 cm AC (Dual)	67.77	57.61	4755.09	3945.63
27	Reconstruction 30 cm Aggregate Base / 16 cm AC (Dual)	69.42	59.01	2318.42	4041.83
28	Reconstruction 20 cm WBM / TST	33.85	28.77	2318.42	1970.65
29	Reconstruction 20 cm WBM / DST	32.87	27.94	2251.25	1913.57
30	Rigid Pavement	55.47	47.15	3799.27	3229.38
31	Existing Surface Treatment With / TST	6.99	5.94	478.73	406.92
	Routine Maintenance	Unit	Financial Cost	Economical Cost	
32	Patching with BITMAC	SM	195.00	165.75	
33	Crack Sealing	SM	12.50	10.63	
34	Cut Vegetation	/Km	18,750.00	15,937.50	
35	Side Drain Cleaning	/Km	37,500.00	31,875.00	
36	Kilometer post Replacement	Each	12,500.00	10,625.00	
	Treatment	Unit	Rate (Rs)	SM Rate with 25% ESC. (Rs)	
37	Patching with BITMAC	SM	156.00	195.00	
38	Crack Sealing	SM	10.00	12.50	
39	Cut Vegetation	/Km	15,000.00	18,750.00	
40	Side Drain Cleaning	/Km	30,000.00	37,500.00	
41	Kilometer post Replacement	Each	10,000.00	12,500.00	

Appendix B MR&R Profiles for MPDC Estimation

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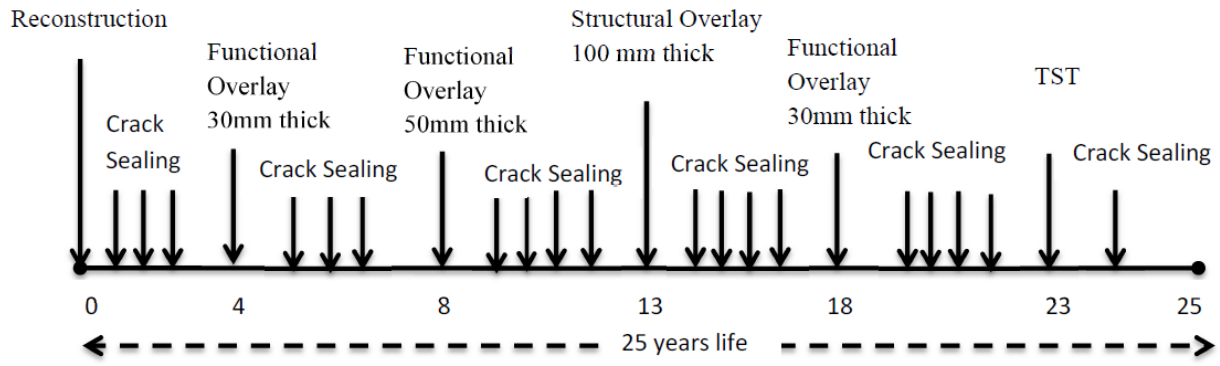

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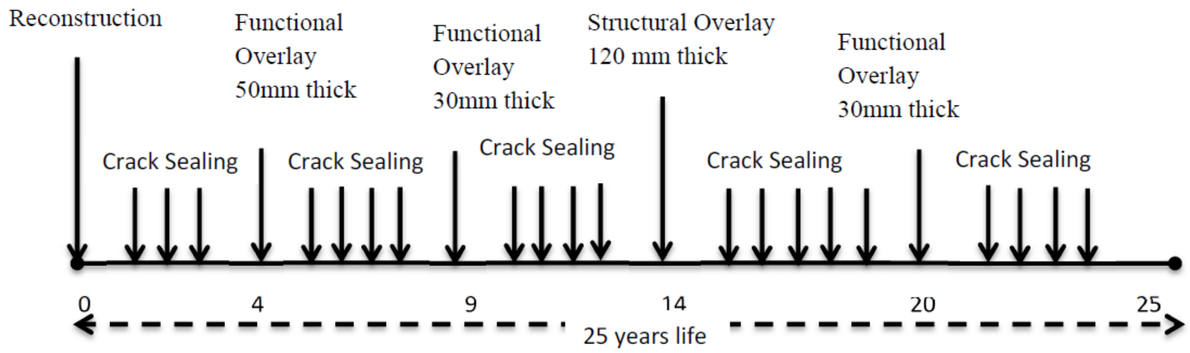

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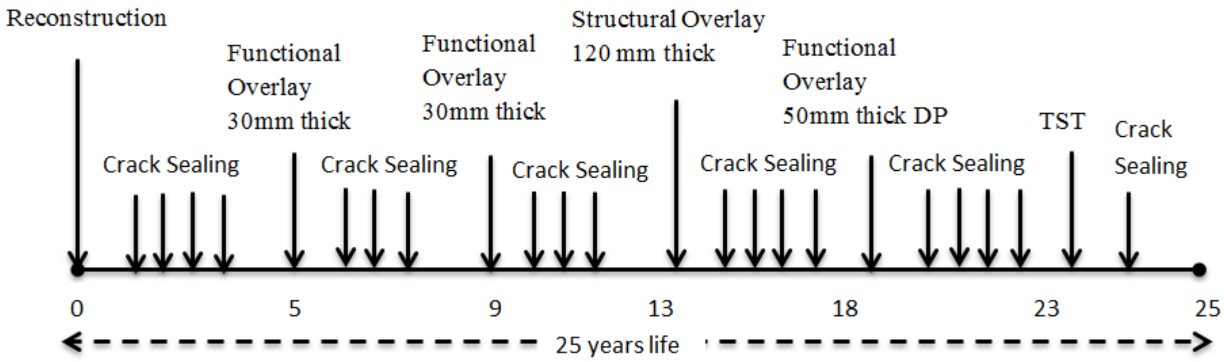

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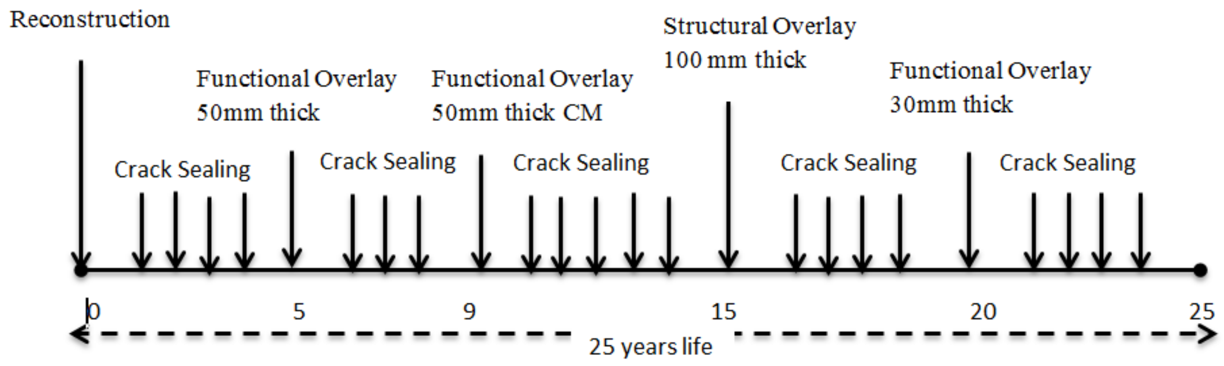

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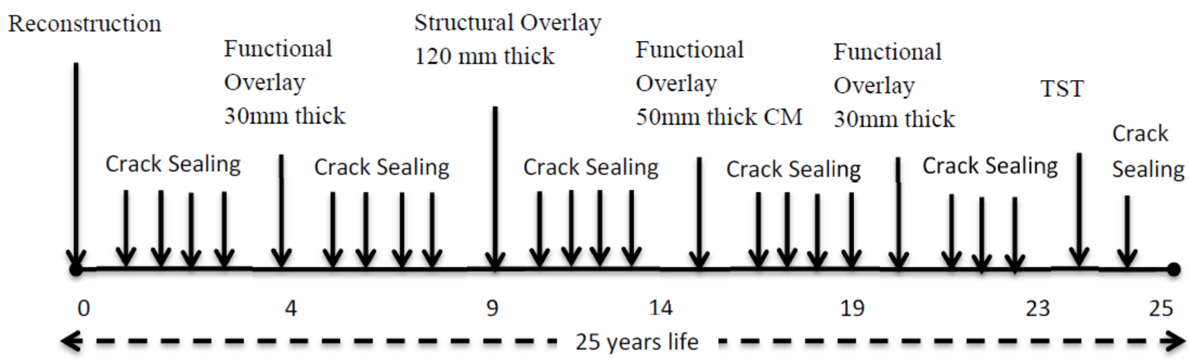

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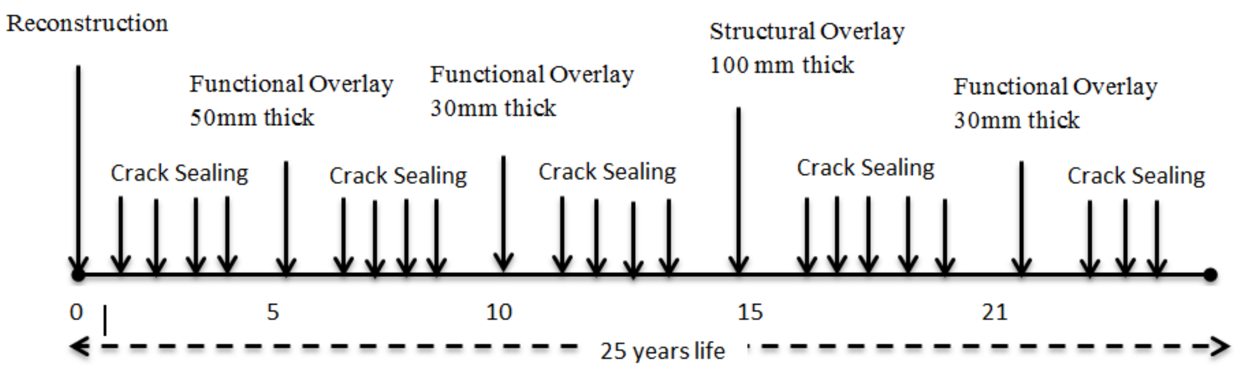

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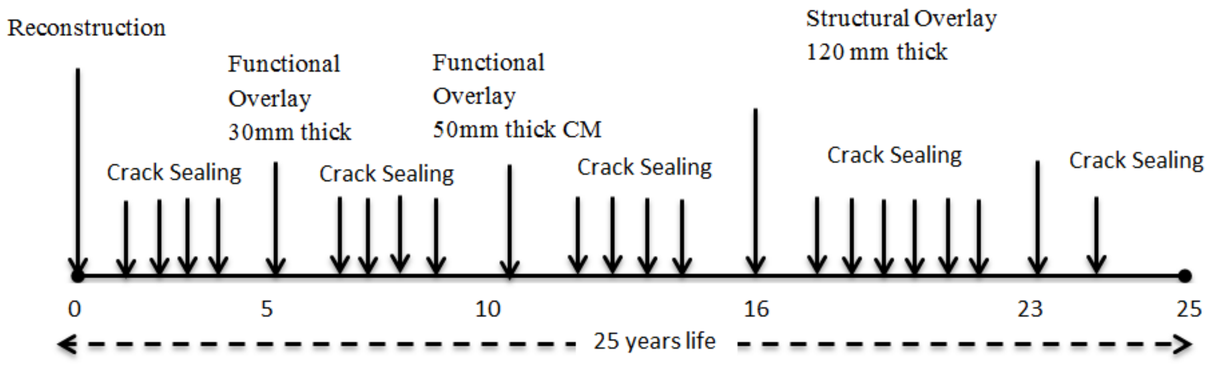

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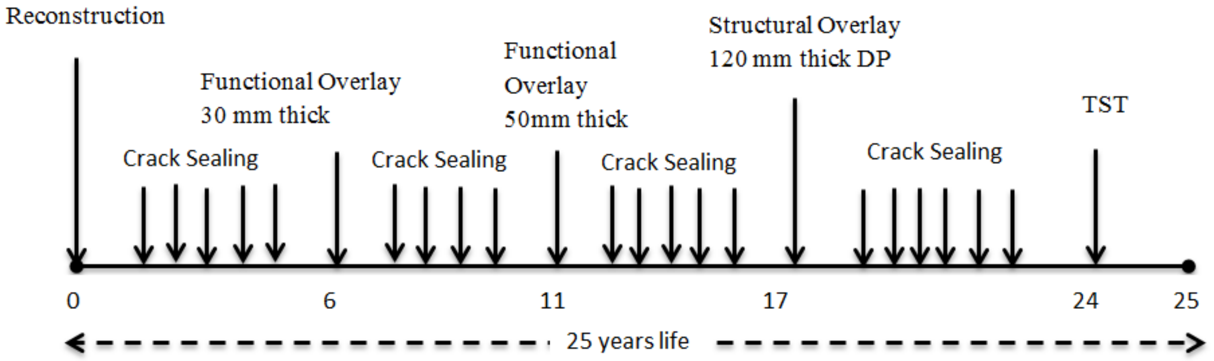

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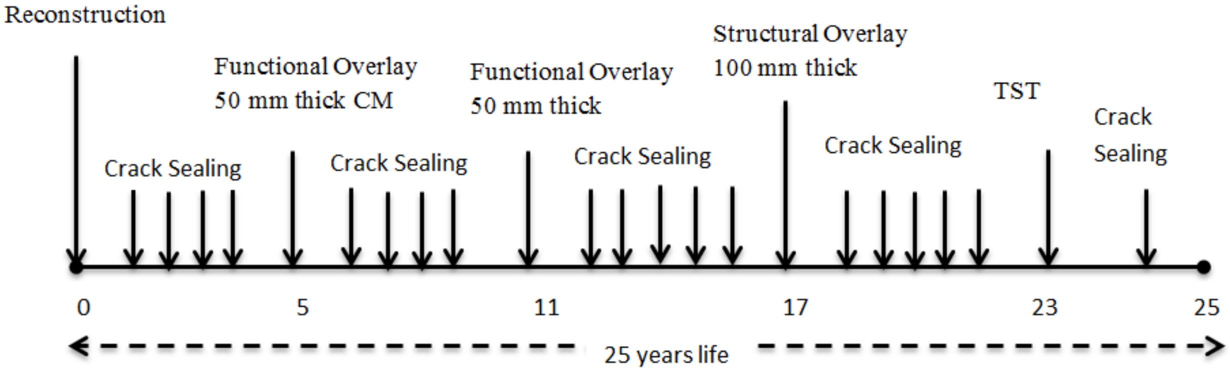

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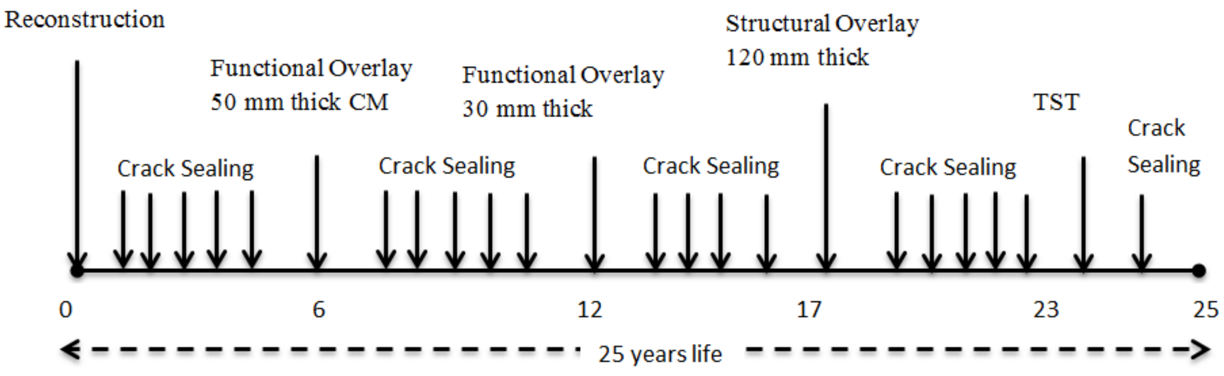

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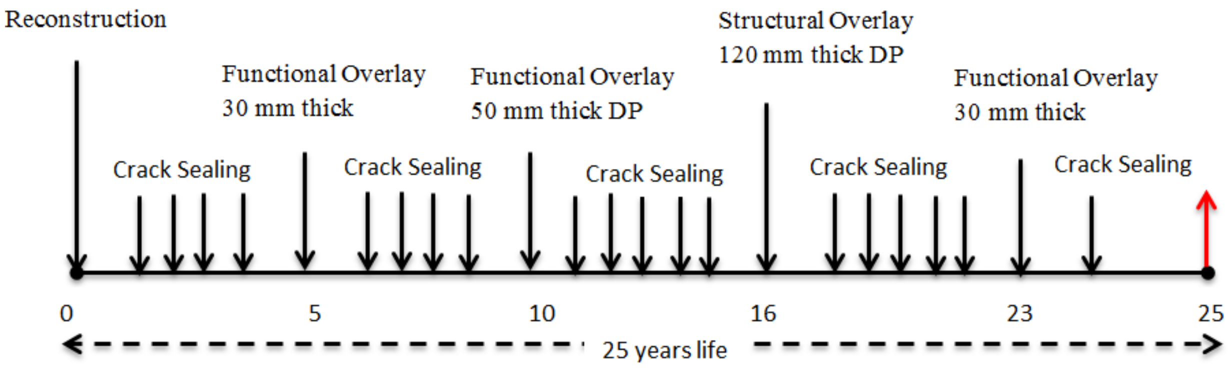

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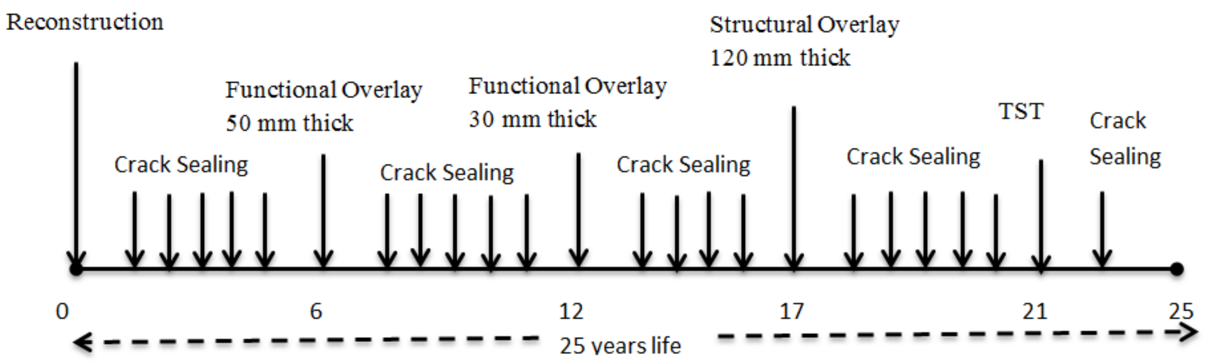

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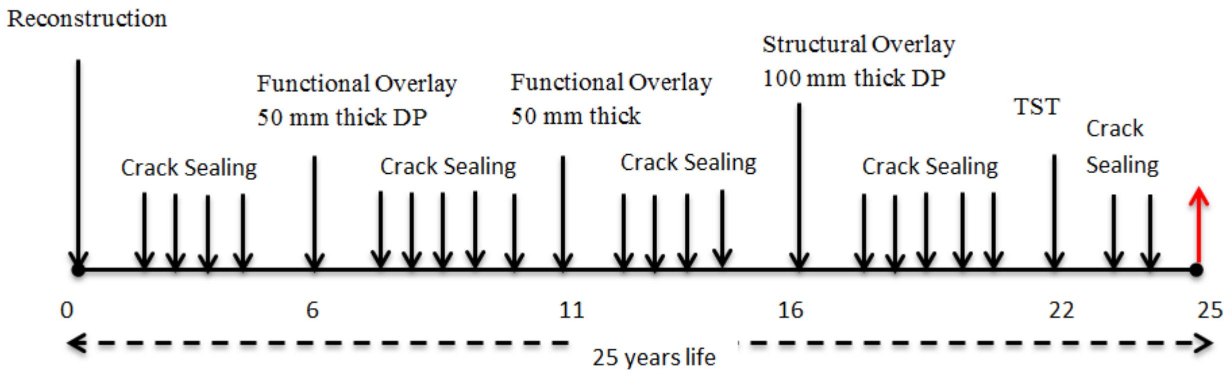

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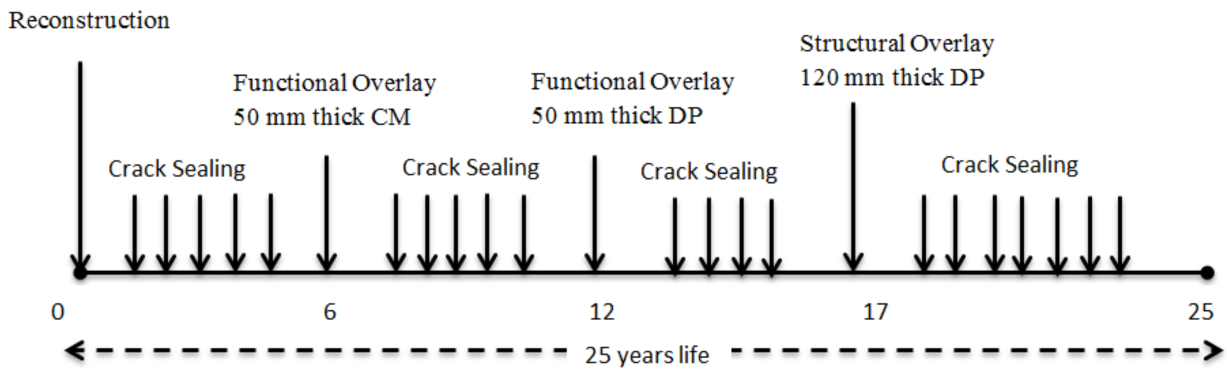

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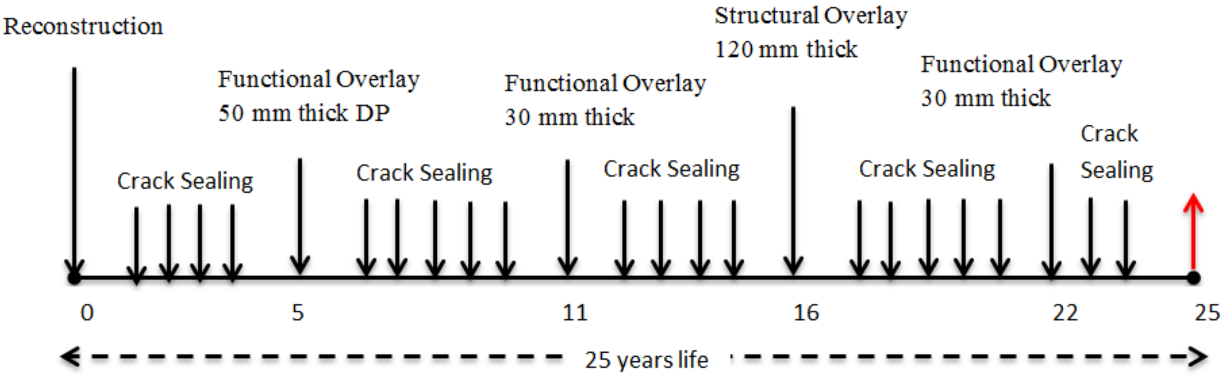

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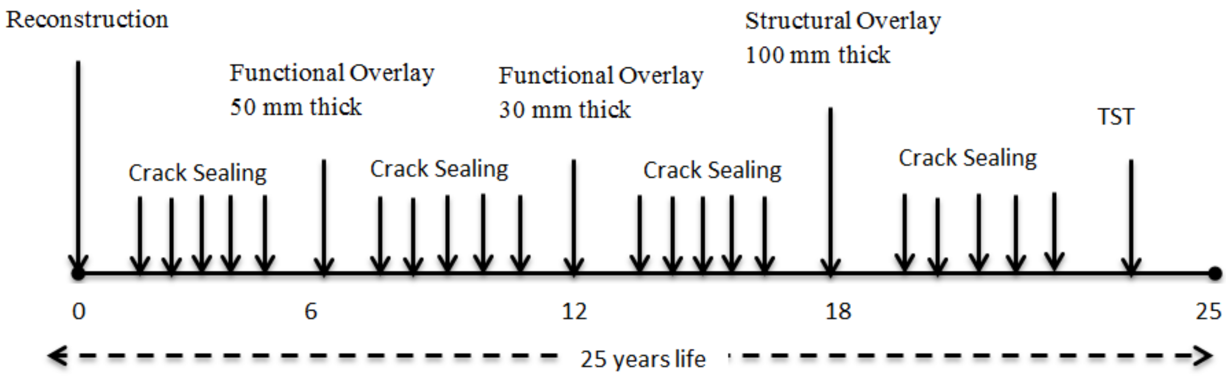

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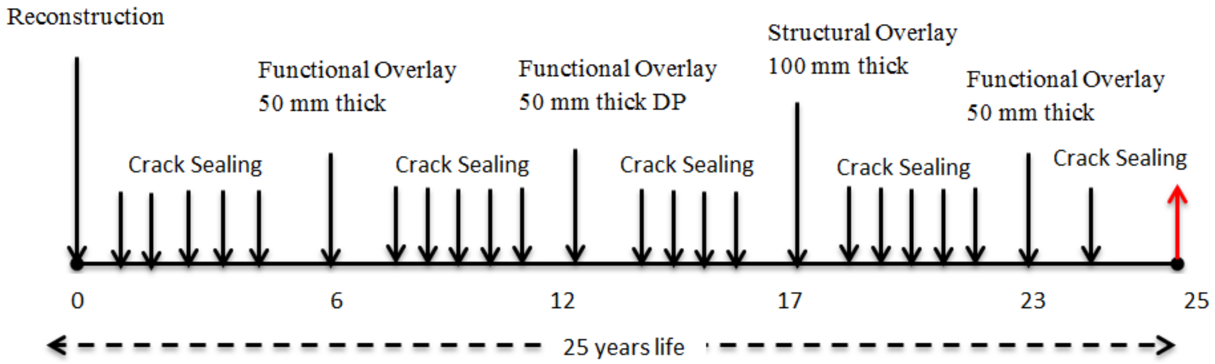

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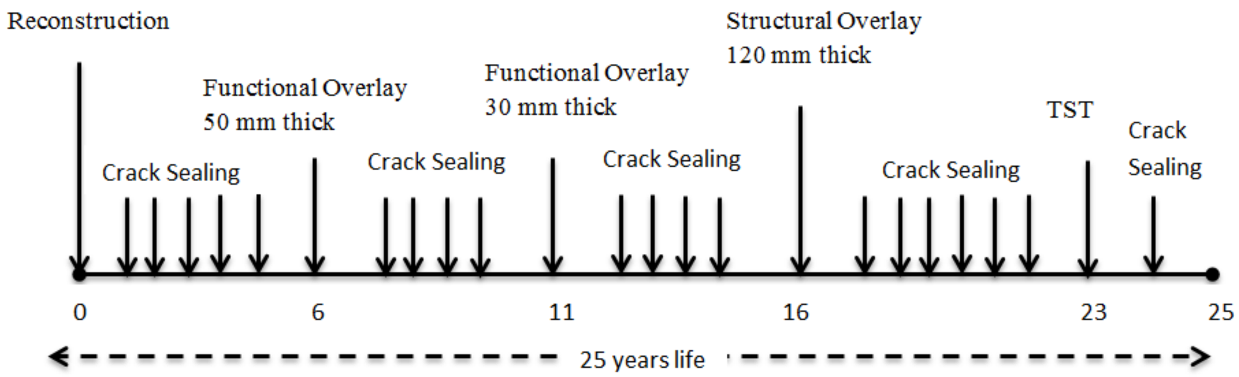

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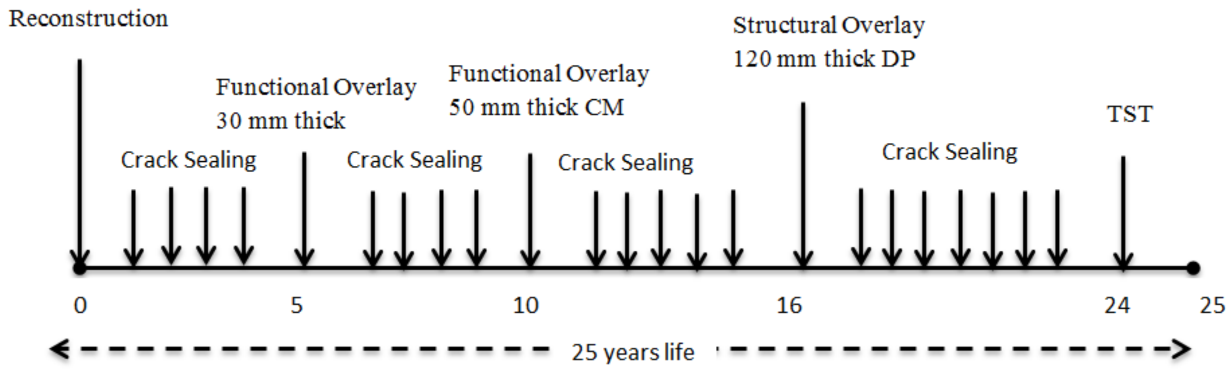

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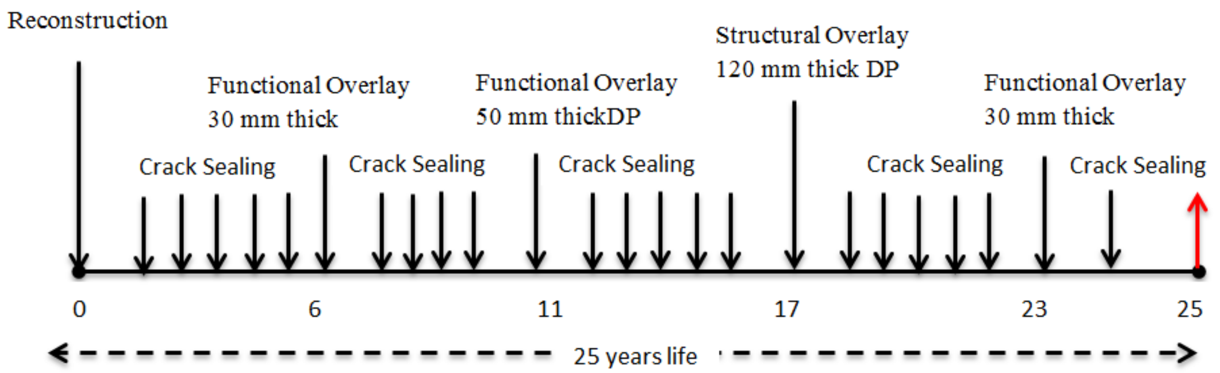

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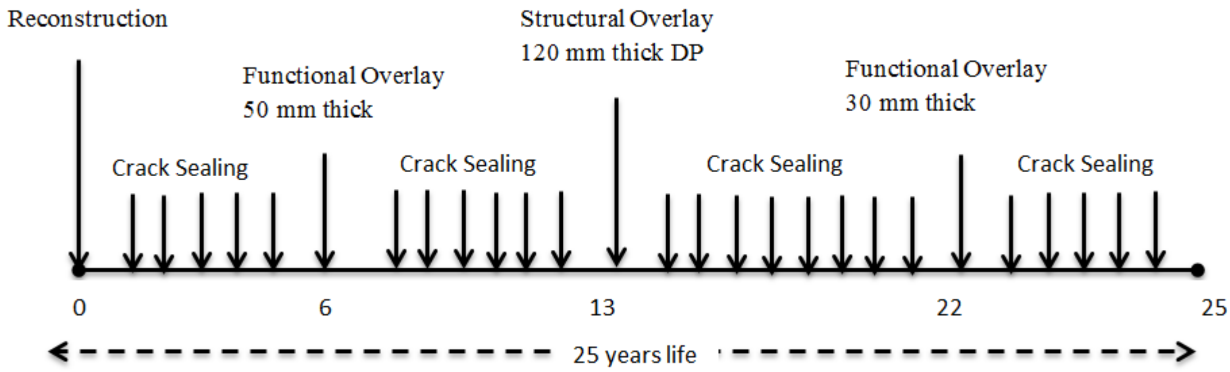

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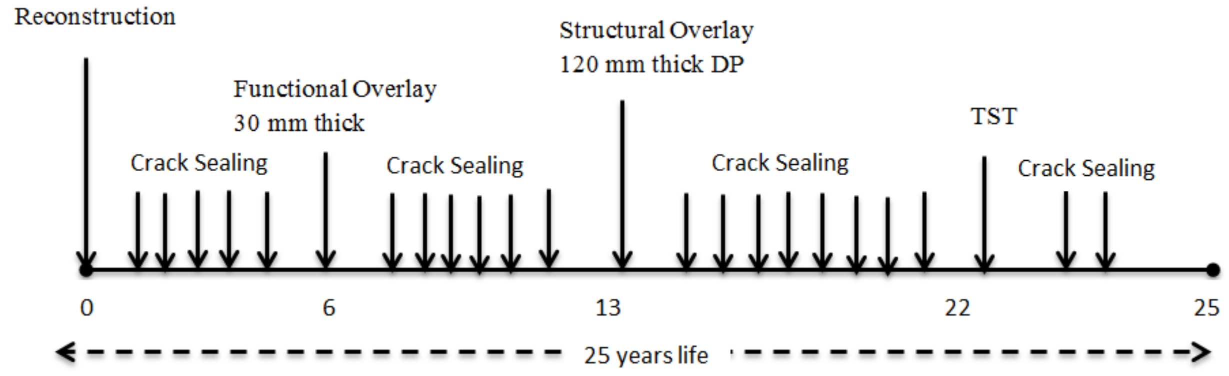

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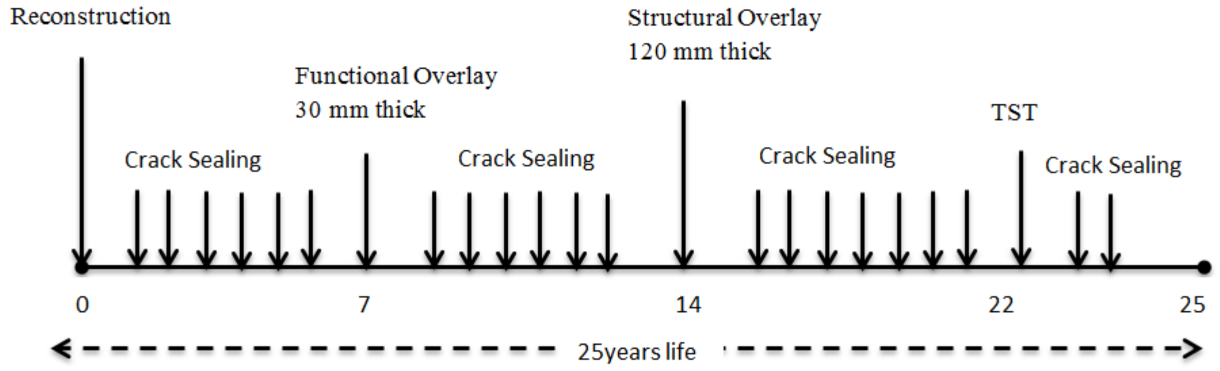

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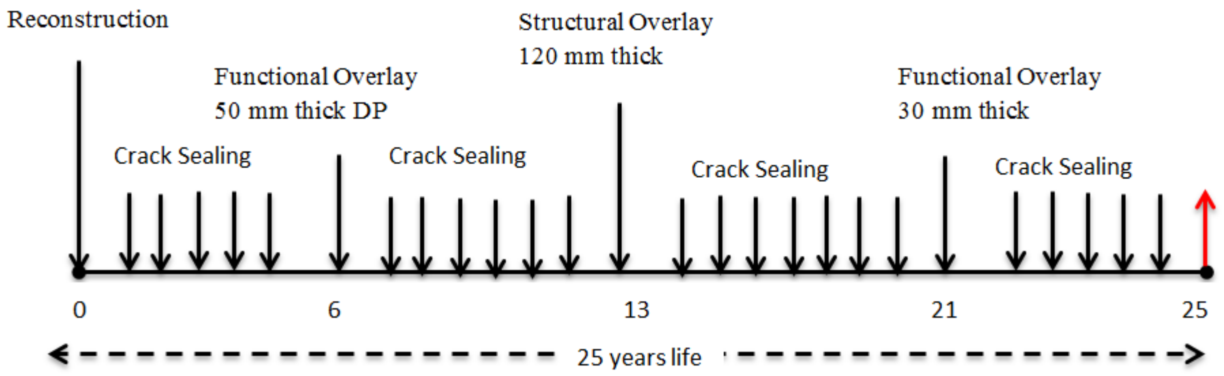

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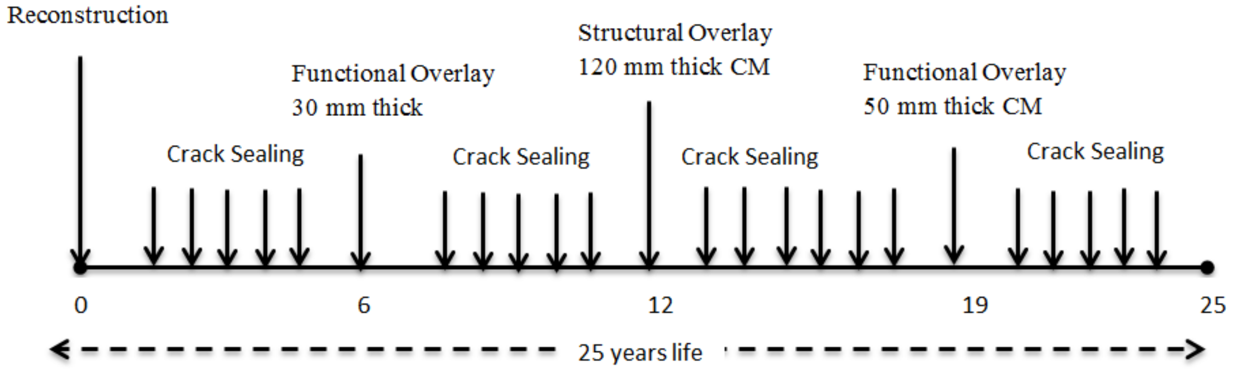

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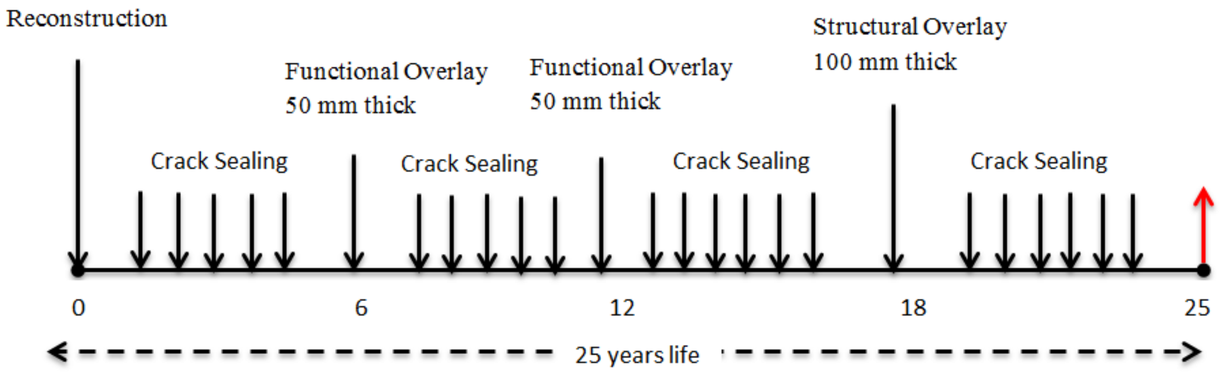

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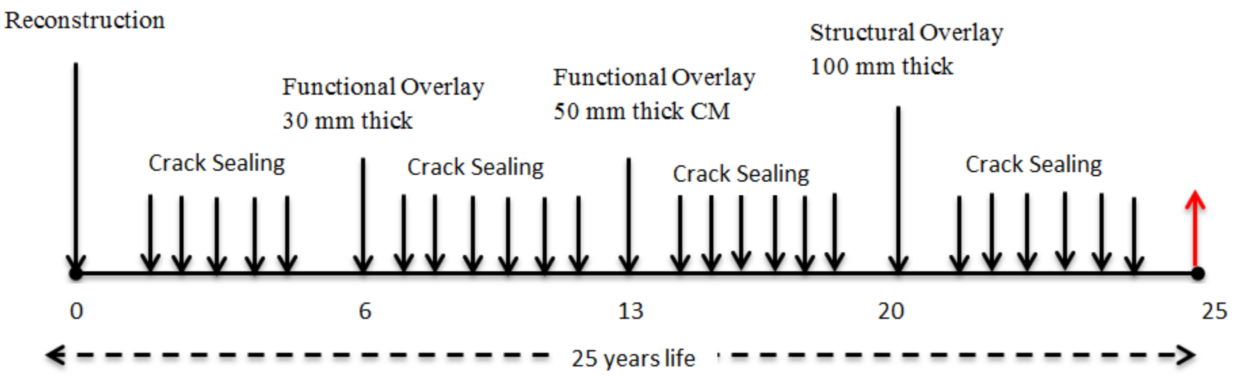

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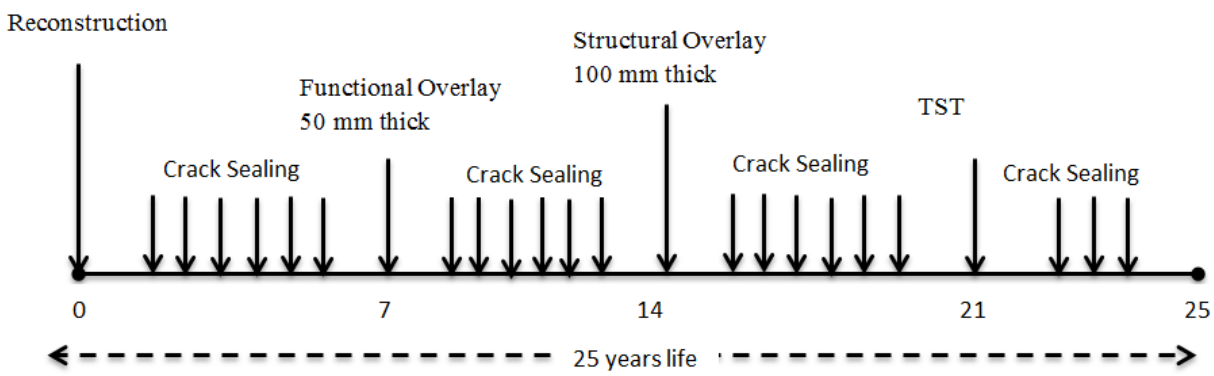
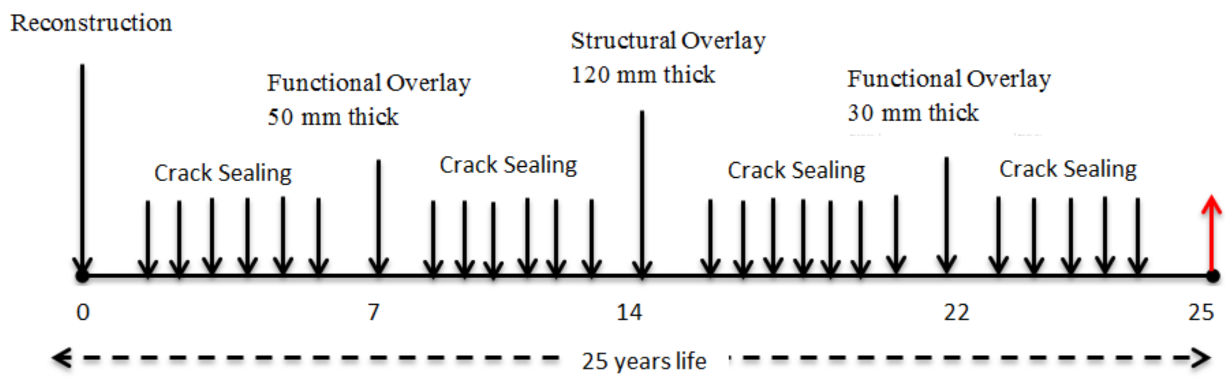


Profile 29:



Profile 30: