Historical Performance Evaluation of Iowa Pavement Treatments Using Data Analytics

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16. Abstract

The pavement network in Iowa has reached a mature state making maintenance and rehabilitation activities more important than new construction. As such, a need exists to evaluate the performance of the pavement treatments and estimate their performance lives to support future maintenance and rehabilitation decisions. This evaluation can be achieved by examining the pavement condition data before and after any treatment method was applied.

However, the pavement condition data for Iowa roads stored in the Iowa Department of Transportation's (DOT's) geographic information system (GIS) were not compatible with the preservation and rehabilitation project data available from the Iowa DOT Office of Contracts. Therefore, this study used GIS tools and methods, such as the Iowa DOT's linear referencing system (LRS) and geoprocessing tools, to spatially integrate the two databases and examine the pavement conditions before and after the application of pavement treatments.

Afterward, data analytics were conducted to evaluate the actual pavement performance information and estimate the service life of each treatment method using different performance indicators. Moreover, pavement performance analysis developed at the distress-level scale found that most of the analyzed segments had irregular patterns in terms of longitudinal cracks, transverse cracks, alligator cracks, and longitudinal cracks on the wheelpaths. On the other hand, the researchers found that rutting and the International Roughness Index (IRI) were the most consistent pavement performance indicators. As such, these two indicators were used to estimate the average service lives of the rehabilitation treatments.

Based on the analysis conducted, hot-mix asphalt (HMA) resurfacing, HMA resurfacing with milling, and HMA resurfacing with cold in-place recycling (CIPR) have longer service lives when the IRI was used as a performance indicator. In addition, HMA resurfacing with CIPR outperformed HMA resurfacing with or without milling when traffic loadings were low.

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EXECUTIVE SUMMARY

The transportation network in the United States has reached a mature state making maintenance and rehabilitation more important than new construction. State highway agencies (SHAs) are directing their available funds more toward maintenance and rehabilitation rather than expanding the existing network. Additionally, agencies are still striving to keep their transportation assets at acceptable levels of service because of issues with limited funding. Thus, a realistic evaluation of existing pavement treatments is needed to smartly improve agency decision-making systems and maximize the benefit from the treatments.

This study used data collected by the Iowa Department of Transportation (DOT) to evaluate the performance of three major treatments used by the Iowa DOT: hot-mix asphalt (HMA) resurfacing, HMA resurfacing with milling, and HMA resurfacing with cold in-place recycling (CIPR). The objectives of this study were to estimate the service lives of those treatments as well as compare their performance when operating conditions were similar.

These objectives were achieved by analyzing the pavement condition data before and after any treatment method was applied. However, the pavement condition data for Iowa roads stored in the Iowa DOT's geographic information system (GIS) was not compatible with the preservation and rehabilitation project data available from the Iowa DOT Office of Contracts. Therefore, this study used GIS tools and methods, such as the Iowa DOT's linear referencing system (LRS) and different geoprocessing tools, to spatially relate these two databases and examine the pavement conditions before and after the application of pavement treatments.

Using data analytics, actual pavement performance over time was evaluated on a distress-level scale. It was found that rutting and the International Roughness Index (IRI) are the most consistent pavement performance indicators. As such, rut depth and the IRI were used to estimate average service lives for the rehabilitation treatments. It was also found that most of the analyzed segments had irregular deterioration patterns in terms of longitudinal cracks, transverse cracks, alligator cracks, and longitudinal cracks on the wheelpaths. Possibly, unrecorded in-house maintenance and pavement condition data recording practices were the main reasons behind those irregular deterioration patterns.

The researchers also found that HMA resurfacing, HMA resurfacing with milling, and HMA resurfacing with CIPR have different service lives according to the performance indicators used for analysis. The research team concluded that the aforementioned treatments have longer service lives if IRI is used as a performance indicator. In addition, HMA resurfacing with CIPR outperforms HMA resurfacing with or without milling when traffic loadings are low.

This report presents a set of recommendations that should be adopted to maximize the benefits of collecting data and evaluating pavement performance.

INTRODUCTION

Problem Statement

The US has the largest transportation network in the world with close to 2.7 million miles of paved roads, which is a key success factor for promoting the nations' economy (U.S. GAO 2008). In an effort to maintain the existing transportation network at an acceptable level of service, state highway agencies (SHAs) are more likely to spend funds on maintenance and rehabilitation than on expanding the existing network

Accordingly, the highway trust fund, established in 1956, is used to fund surface transportation programs using user taxes. In 2013, the Federal Highway Administration (FHWA) received about $41 billion for the construction, reconstruction, and improvement of highways and bridges according to the FHWA eligibility criteria (U.S. GAO 2014). However, 32 percent of these FHWA funds were used for road resurfacing, rehabilitation, and reconstruction while only 5 percent were used for new construction. This percentage of spending on road rehabilitation and resurfacing emphasizes the importance of these activities and indicates that the US transportation network has reached a mature state where maintenance and rehabilitation are more important than new construction.

Several rehabilitation treatments are available to restore the functional and structural performance of existing pavement. The choice to apply a specific rehabilitation treatment is governed by several factors, such as the pavement's existing condition, funding availability, and treatment performance. Treatment performance significantly affects the economic value of the pavement and hence is considered an influential factor in the selection process when several treatments are technically feasible (Flannery et al. 2016). As such, a realistic treatment performance evaluation is needed to improve existing transportation asset management practices.

Rehabilitation and maintenance treatments are meant to extend the pavement service life by addressing existing pavement distresses, and it is important for pavement managers to know the extended service life or treatment application benefits based on different factors, such as pretreatment conditions, volume of traffic, and type of treatment.

This extended service life results from treatment applications that can be measured using different performance indicators such as pavement distresses, roughness, or friction. For example, pavement roughness indicates the pavement ride quality, which directly affects user ride quality and costs; hence, keeping pavement roughness below a specific threshold value is important to achieving user satisfaction and minimizing user costs. Similarly, other performance indicators are used to measure a treatment's effectiveness in terms of pavement functionality, safety, and ride quality. The choice of which performance indicator is used for performance evaluation depends on the data collected by state highway agencies (SHAs) and their decision-making practices.

By using data collected by SHAs to assess the performance of different treatment methods, it is possible to transform agencies' decision-making/support systems from engineering judgement to data-driven and evidence-based systems. However, the use of data collected by SHAs is associated with technical difficulties that can hinder the performance evaluation process.

Research Objectives

The main objective of this research was to evaluate the performance of the most-used treatments in Iowa by considering different parameters such as type of treatment, treatment thickness, traffic, and pavement type. Additionally, the study aimed at estimating a service life for each treatment based on the observed historical data. To achieve the main objective, pavement condition data and treatment locations needed to be spatially integrated and technical difficulties associated with the data integration process between different sources needed to be overcome. The study also aimed to compare the performance of different treatments under similar conditions.

Research Methodology

First, the performance evaluation of different pavement treatments applied in Iowa was conducted by developing a framework that spatially integrated the pavement data from different sources together. Figure 1 summarizes the framework developed to achieve the main goal of the study.

As shown in Figure 1, the pavement condition data and the treatment project data came from two different sources. The first database was extracted from the Iowa Department of Transportation's (DOT's) Pavement Management Information System (PMIS) while the second database was extracted from the pavement maintenance and rehabilitation contracts stored in the Iowa DOT Office of Contracts.

The PMIS contains most of the information about the highway system such as pavement type, thickness, materials, treatment projects, and traffic. However, the PMIS does not include the treatment type or the length of the project. This missing information is contained in the rehabilitation and maintenance contract database.

The first step in the developed framework was to spatially integrate the two databases together to form a master database that included pavement condition data before and after treatment application, type of treatment, and pavement and traffic information. By using data analytics tools and techniques, the performance of pavement treatments was evaluated and tested using statistical significance testing.

Finally, the research presented two important outputs that would benefit pavement managers and researchers: individual distress deterioration patterns that could help pavement managers understand how distress propagation fits into different severity levels and an estimated service life of each pavement treatment evaluated.

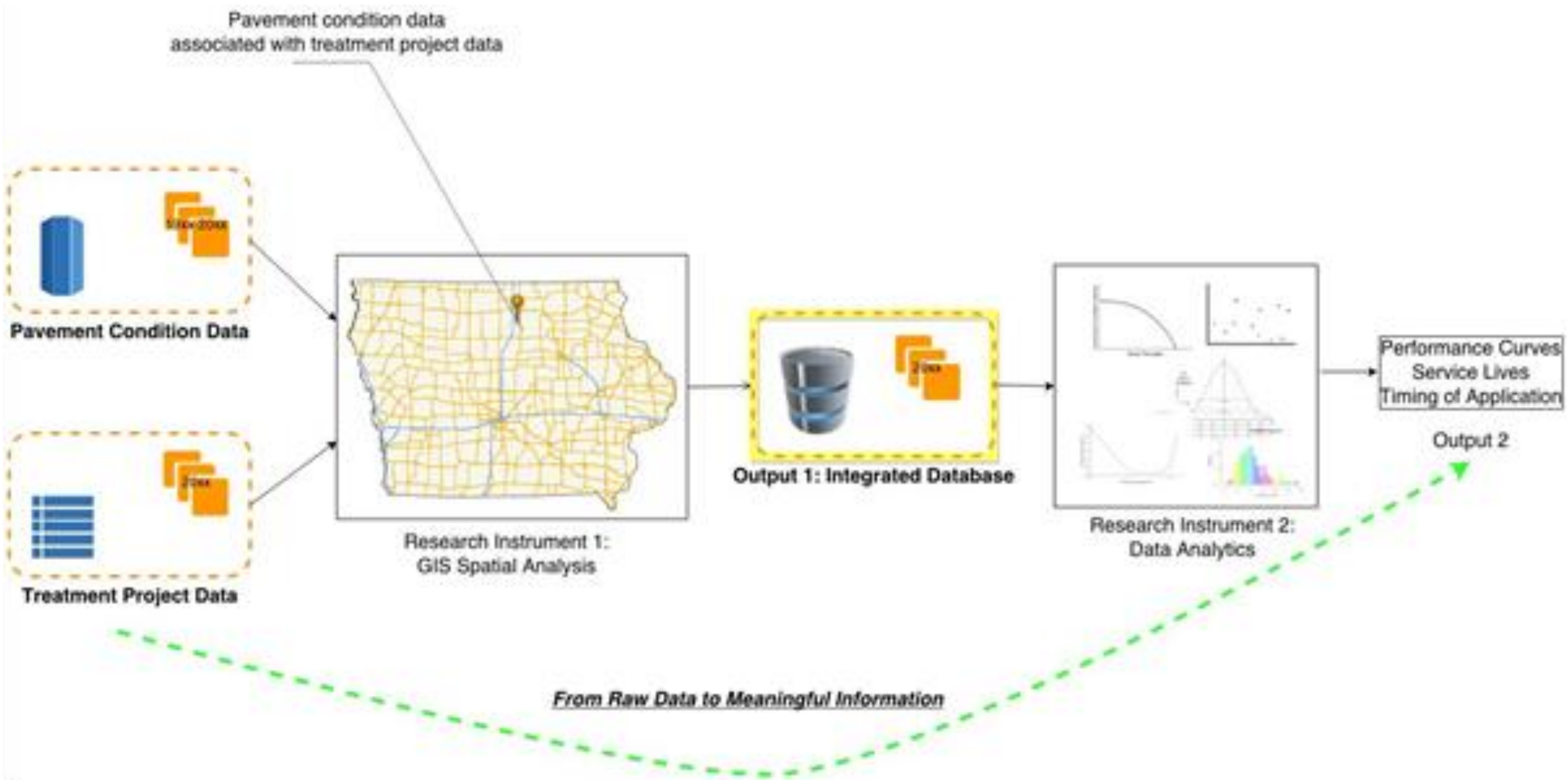

Figure 1. Treatment performance evaluation framework

LITERATURE REVIEW

Many studies have evaluated the performance of pavement maintenance and rehabilitation treatments. The researchers found that the sources of data, treatment types, performance indicators, and statistical methods were the key differences between past studies.

Some studies used data from the Long-Term Pavement Performance (LTPP) program database while others used data collected by SHAs. Treatment types vary between preservation, maintenance, and rehabilitation for composite, flexible, and rigid pavements. The type of treatments evaluated were subject to the number of data collected and interest in specific treatments by agencies and researchers. The performance indicators used in the evaluation were generally the International Roughness Index (IRI), pavement condition rating (PCR), structural number (SN), fatigue cracking, and rutting depth. The researchers also found that the use of specific performance indicators was governed by the data collected by SHAs.

In this chapter, past studies aimed at evaluating the performance of different pavement performance are analyzed. Table 1 summarizes past related studies, sources of data, treatments analyzed, performance indicators used, and number of segments or test sections studied.

Table 1. Past related studies summary

Study	Data Source Location	Treatments	Performance Indicators	Number of Sections Analyzed
Hall et al. 2002	LTPP nationwide	Thin/thick overlay, slurry seal, crack seal, and chip seal	IRI, rutting, and fatigue cracking	81 for maintenance and 18 for rehabilitation
		Asphalt overlay for rigid pavements		14
Chen et al. 2003	LTPP in Texas	Thin overlay, slurry seal, crack seal, and chip seal	Distress score developed by Texas DOT	14 test sections
Broughton and Lee 2012	Texas DOT	Microsurfacing	Various distresses/visual inspection	4 segments
Irfan et al. 2009	Indiana DOT	Functional/structural (hot-mix asphalt (HMA) overlay, resurfacing of existing pavement, and milling with overlay	IRI	From 41 to 62 according to treatment type
Shirazi et al. 2010	LTPP nationwide	Thin overlay, slurry seal, crack seal, and chip seal	A weighted average index representing fatigue cracking, rutting, and IRI	81 segments
Labi et al. 2007	Indiana DOT	Microsurfacing	IRI, PCR, and rutting	18 segments
Labi and Sinha 2004	Indiana DOT	Seal coat	Present serviceability index (PSI)	35 segments
Lu and Tolliver 2012	LTPP nationwide	Patching, mill with overlay, crack sealing, aggregate seal, seal coat, and chip seal	IRI	135 for mill with overlay, 97 for aggregate seal, 317 for crack sealing, and 13 for chip seal
Ji et al. 2012	Indiana DOT	Microsurfacing	PCR, IRI, and SN	4 sections

Study	Data Source Location	Treatments	Performance Indicators	Number of Sections Analyzed
Dong and Huang 2012	LTPP nationwide	Overlays with/without recycling materials, overlays with milling	IRI	318 for HMA overlay, 43 for HMA overlay with recycled asphalt, 100 for HMA overlay with milling, and 58 HMA overlay (recycled asphalt) with milling
Chen et al. 2010	Iowa DOT	Cold in-place recycling (CPR)	Pavement Condition Index (PCI) and falling weight deflectometer (FWD) measurements	24 sections
Kim et al. 2010	Iowa DOT	Cold in-place recycling	PCI individual distresses	26
Jahren et al. 1998	Iowa DOT	Cold in-place recycling	PCI and PSI	18 sections
Hong et al. 2010	LTPP in Texas	Recycled asphalt pavement with asphalt overlay	Transverse cracking, rut depth, and ride quality	8 sections (4 virgin and 4 recycled asphalt concrete (AC))
Liu et al. 2010	Kansas DOT	Seal coat, slurry seal, cold in-place recycling, and overlays	Time between consecutive treatments	Varies
Wang et al. 2011	LTPP in several states	Thin overlay, chip seal, crack seal, and slurry seal	IRI	81 segments

Sources of Data

The two main sources of data used in evaluating the performance of pavement treatments are as follows:

- LTTP program database
- Pavement condition data collected by SHAs

The LTPP program, initiated in 1987, represents an important source of pavement performance information (FHWA 2016). The LTPP program has an inventory of material testing; pavement performance monitoring; as well as climate, traffic, maintenance, and rehabilitation data for more than 2,500 test sections located in the United States and Canada (FHWA 2016).

Many studies used the LTPP program data to analyze the performance of different pavement treatments. For example, Hall et al. (2002), Shirazi et al. (2010), Lu and Tolliver (2012), Wang et al. (2012), and Dong and Huang (2012) used the LTPP program data at a nationwide scale to analyze the performance and effectiveness of several pavement treatments. On the other hand, Chen et al. (2003) and Wang et al. (2011) used the LTPP program data to analyze treatment performance at a statewide scale.

The use of LTPP program data in performance evaluation at the nationwide level is beneficial because of the large number of sections stored in the LTPP program database. However, for some states, using the LTPP program data at the state level might not be as reliable as using the LTPP program data at the nationwide level because of the small number of data collected at the state level. For example, Iowa has data for only 66 test sections, which is a very small population, especially since the data are only classified by pavement type and type of treatment. Thus, there is a need to utilize the data collected by SHAs at the state level to best evaluate the performance of pavement treatments.

Few studies used data collected by SHAs to evaluate specific treatments that were newly adopted by the agency. For example, Labi et al. (2007) and Ji et al. (2012) evaluated the performance of microsurfacing in Indiana by using condition data collected from closely monitored sections. Condition data for these sections were collected annually using visual surveys and nondestructive tests.

In Indiana, Irfan et al. (2009) used data collected by the Indiana DOT to evaluate the performance of HMA overlays. In Kansas, Liu et al. (2010) used data from Kansas DOT’s PMIS to evaluate the performance of thin surface treatments in Kansas. It is worth mentioning that the database used in the studies conducted by Labi et al. (2007) and Irfan et al. (2009) contained data about pavement referencing, pavement condition, traffic volume, freeze-index, and preservation contracts data, and the Kansas DOT’s PMIS contained traffic, pavement condition, and pavement referencing data.

Pavement Treatment Types

There has been a growing interest in evaluating the effectiveness of preservation, maintenance, and rehabilitation treatments to justify their economic effectiveness and establish guidelines for measuring their effectiveness for budgeting purposes. As such, the performance of several maintenance and rehabilitation treatments such as slurry seal, crack seal, chip seal, microsurfacing, patching, cold in-place recycling, and HMA overlay have been evaluated at the national and state levels (Hall et al. 2002, Chen et al. 2003, Broughton and Lee 2012, Irfan et al. 2009, Shirazi et al. 2010, Labi et al. 2007, Lu and Tolliver 2012, Ji et al. 2012, Chen et al. 2010, and Dong and Huang 2012). It was found that the selection of what treatments to evaluate is governed by data availability and SHA policies. For instance, some SHAs apply new treatments for a period of time and then start to evaluate the performance of those treatments to improve their future decisions.

Performance Indicators

There are several performance indicators used to evaluate the performance of maintenance and rehabilitation treatments such as IRI, PCR, rut depth, and fatigue cracking (Hall et al. 2002, Irfan et al. 2009, Labi et al. 2007, Wang et al. 2011, and Lu and Tolliver 2012). Additionally, other studies used performance indicators that were developed by SHAs such as the distress score developed by the Texas DOT (Chen et al. 2003) while other studies presented a weighted average index that combined several distresses (Shirazi et al. 2010).

Chen et al. (2003) used the distress score concept developed by the Texas DOT to evaluate treatment effectiveness in Texas. The distress score quantifies the visible surface deterioration of pavements and was computed as a function of utility values for rutting; patching; and block, alligator, longitudinal, and transverse cracking.

Hall et al. (2002) used road roughness level or ride quality, measured in IRI, to evaluate performance since it was found to be an influential factor that affects overlay treatments. Moreover, Irfan et al. (2009) linked the used IRI for treatment performance evaluation because of its use for pavement preservation decisions and because it was found to be collected on a regular basis. On the other hand, some studies selected IRI as a performance indicator because the treatments under evaluation were expected to address minor distresses and improve ride quality (Labi et al. 2007 and Lu and Tolliver 2012).

Labi and Sinha (2004) used the present serviceability index to evaluate the performance of seal coats in Indiana. The study acknowledged that PSI may not be the most ideal performance indicator since the PSI is directly associated with ride quality. However, the study used the PSI instead of the PCR because of the lack of PCR data. This points out the issue that data collection and sufficiency of data collected will directly affect the performance evaluation process and the performance indicators used to evaluate treatment performance.

Similarly, rut depth was used as a performance indicator to measure the effectiveness of specific treatments on reducing rutting for the short and long term (Labi et al. 2007). Additionally, fatigue cracking was also used to measure treatment effectiveness in terms of the percent of section area cracked before and after treatment application (Hall et al. 2002).

Beside using individual performance indicators to measure performance, Labi et al. (2007) used the PCR in performance evaluation to represent the overall user perception of road quality. Similarly, Chen et al. (2010) used the PCI as an overall indicator of pavement performance to evaluate the pavement performance after applying cold in-place recycling treatment. Additionally, Chen et al. (2010) used the FWD measurements to calculate the dynamic moduli of pavement layers and hence evaluate the structural performance of pavements. The use of overall indexes that aggregate different distresses into one score such as PCR and PCI can be misleading because several cases of existing distress severity and extent can yield the same score. For example, a pavement with high severity and extent alligator cracking can possibly have a similar score to another pavement with moderate to low severity and an extent level for several other distresses. For that reason, one PCI score can yield several different variations of distress severity and extent. As such, Kim et al. (2010) used individual distress types to evaluate the performance of cold in-place recycling in Iowa. The study found that the measurement of individual distresses can decrease over time because cracks might have been changed from one type to another and/or there were errors in the measurements.

While many studies used common performance indicators to evaluate the performance of treatments, Liu et al. (2010) used the time between two consecutive treatments or time between treatment application and reconstruction to estimate the service life of thin surface treatments. The methodology adopted by Liu et al. (2010) reflects the SHAs policy and experience on the estimation of treatment performance. However, it should be noted that this methodology does not consider the delay in consecutive treatment applications due to funding gaps.

Finally, a study by Broughton and Lee (2012) used visual inspection of distresses to evaluate the effectiveness of a treatment. Visual inspection is a subjective method that cannot be relied on to evaluate the effectiveness of a treatment. However, visual inspection is the only available method that can be used to evaluate pavement performance when no data are available.

Statistical Methods

Past researchers used statistical significance testing to evaluate the performance of several treatments. Labi and Sinha (2004), Labi et al. (2007), and Lu and Tolliver (2012) used a one-sided hypothesis test to examine the statistical significance of the estimated performance jump at 95 percent level of confidence while Ji et al. (2012) used the analysis of variance (ANOVA) test to compare the SN and IRI statistical difference before and after treatment application. It is worth mentioning that the aforementioned tests assume a normal distribution of the means of population, which is not necessarily true in some cases. However, this assumption is considered not to be violated when the sample size used is large (i.e., greater than 30).

Hong et al. (2010) used a paired t-test to compare roughness levels of recycled asphalt pavement versus virgin asphalt pavements. Wang et al (2011) also used the paired t-test to evaluate the effectiveness of pavement treatments by analyzing the IRI measurements between control sections and sections that received specific treatment.

On the other hand, Shirazi et al. (2010) recognized the assumptions associated with parametric tests such as the ANOVA and paired t-tests and hence used the Friedman test, a non-parametric test, to evaluate treatment performance.

Differently, Dong and Huang (2012) utilized a multiple regression method to evaluate the effectiveness of asphalt pavement rehabilitations by considering overlay thickness, pavement thickness, traffic volume, and pretreatment conditions. Chen et al. (2010) also used multivariate regression to investigate the cause and effect relationships between the pavement performance and influential factors such as cumulative traffic, support condition, and recycled material properties.

Performance Evaluation

Past studies used different sources of data and methods to estimate the service lives of maintenance and rehabilitation and determine positive and negative influential factors. In this section, a summary of findings from past related studies is presented.

Hall et al. (2002) concluded that the following factors have an effect on flexible pavement HMA overlay performance:

- Pretreatment IRI has significant effect on post-treatment IRI
- Age and average annual temperature has slightly significant effects on IRI
- Equivalent single-axle loads (ESALs) have no significant effect on IRI
- Age has the most significant effect on rutting
- Average annual precipitation has a slightly significant effect on rutting
- Pretreatment cracking has a very significant effect on alligator cracking
- Age and ESALs have slightly significant effects on alligator cracking

Similarly, Hall et al. (2002) concluded that accumulated ESALs and pre-treatment IRI had significant effects on post-treatment IRI for rigid pavement HMA overlay.

Chen et al. (2003) used the LTPP program data in Texas to evaluate the performance of thin overlay, chip seal, crack seal, and slurry seal. It was found that chip seal is the best performer for low- and high-traffic areas and thin overlay is the most effective treatment to address rutting (Chen et al. 2003).

In Indiana, Irfan et al. (2009) estimated the service life of rehabilitation treatments based on the critical threshold value concept, which indicated that the service life of a treatment can be terminated when the critical threshold value is reached. Irfan et al. (2009) also estimated the service life of rehabilitation treatments based IRI critical threshold values:

- 8 years for HMA overlay functional
- 9 years for HMA overlay structural
- 10 years for resurfacing of existing asphalt pavement
- 9 years for mill full-depth and asphaltic concrete overlay

It was also concluded that traffic loading levels and climatic severity significantly affected the service lives of rehabilitation treatments (Irfan et al. 2009).

Labi and Sinha (2004) evaluated the effectiveness of seal coats using the PSI as a performance indicator. The study concluded that seal coats can enhance pavement performance by an average of 0.23 PSI units. Additionally, seal coats can retard the level of pavement deterioration by an average of 3.38 PSI units per year.

Additionally, Labi et al. (2007) and Ji et al. (2012) evaluated the effectiveness of microsurfacing. Labi et al. (2007) concluded that microsurfacing can improve pavement performance as follows:

- Reduce the IRI by 28 in./mi (0.442 m/km) on average
- Reduce rutting by 5/32 in. (4 mm) on average
- Improve the PCR by 6.2 units

Labi et al. (2007) also determined the following factors as influential factors on microsurfacing performance:

- Pretreatment condition
- Freeze index
- Traffic
- Pavement class

Ji et al. (2012) conducted a structural evaluation of pavements by using the SN to accurately evaluate the performance and life extension of microsurfacing. The study concluded the following:

- Microsurfacing is not effective in terms of increasing pavement SN
- Microsurfacing can offer a life extension from 1 to 1.5 years in terms of SN, 2 to 3 years in terms of IRI, and 8 years in terms of rutting
- Resurfacing can offer a life extension from 1 to 2 years in terms of SN, 8 to 10 years in terms of IRI, and 10 to 15 years in terms of rutting

The study also estimated the service life of microsurfacing based on different performance indicators. Microsurfacing had a service life of 2 to 10 years for IRI, over 10 years for rutting, and 4 to 15 years for PCR. Service lives are estimated based on the time elapsed by the pavement to revert to the pretreatment condition or a specific condition trigger (Labi et al. 2007). It is worth noting that the service lives estimated by Labi et al. (2007) were calculated using performance models developed by the Indiana DOT and not actual historical data.

Shirazi et al (2010) evaluated the performance of thin overlay, slurry seal, chip seal, and crack seal in terms of mitigating the rate of distress propagation. Based on the analysis of 81 segments obtained from the LTPP program database, the following conclusions were made (Irfan et al. 2009):

- Thin overlay and chip seal are effective in mitigating fatigue cracking propagation
- Thin overlay is the best performer in terms of mitigating rutting and roughness problems
- Climate condition, traffic, subgrade materials, and pretreatment condition had slightly to no effect on treatments with respect to rutting mitigation

Based on the LTPP program database, Lu and Tolliver (2012) concluded that IRI short-term effectiveness followed a polynomial relationship with the pretreatment condition. The study also concluded that the short-term IRI performance jump for several treatments was as follows:

- 0 to 164.73 in/mi (2.6 m/km) for hot mill overlay
- 0 to 27.87 in/mi (0.44 m/km) for crack sealing
- 0 to 91.23 in/mi (1.44 m/km) for aggregate seals
- 0 to 76.03 in/mi (1.2 m/km) for chip seal

Similarly, Dong and Huang (2012) used the LTPP program database to evaluate the effectiveness of asphalt pavement rehabilitation treatments. The service life of a treatment was defined as the time from treatment application to the next rehabilitation treatment application. Based on this definition, the study estimated the average service lives for rehabilitation treatments based on ride quality performance or IRI:

- 9.7 years for HMA overlay
- 9.3 years for HMA overlay with milling
- 9.7 years HMA overlay (recycled asphalt) with milling

Additionally, Dong and Huang (2012) used a regression model to evaluate the influence of various factors on treatment effectiveness:

- Traffic level, pretreatment roughness, and rate of roughness increase before treatment application are influential factors on pavement performance after treatment application
- Using reclaimed material (30%) does not affect the treatment effectiveness
- Thick overlay and milling will positively affect the post-treatment roughness

Wang et al. (2011) also used the LTPP program database to evaluate the performance of several treatments against control sections. It was concluded that pavement treatment can extend pavement service life as follows:

- 5.4 years for thin overlay
- 1.9 for chip seal
- 1.7 years for crack seal
- 1.1 for slurry seal

In Iowa, Jahren et al. (1998) evaluated the performance of cold in-place recycling using the PCI and PSI. The researchers reported the predicted service life of cold in-place recycling using regression analysis as 14 to 29 years in terms of PSI and as 14 to 38 in terms of PCI. The study used these average indexes to estimate the service life of cold in-place recycling. Based on a failure threshold value of 25, the predicted service life of cold in-place recycling was from 15 to 26 years.

INTEGRATION OF DATASETS

Data Integration Framework

Two primary sources of information were used in the study:

- Pavement treatment contracts data from the Iowa DOT Office of Contracts
- Raw pavement condition data from the Iowa DOT

Pavement Treatment Contracts Data

The pavement treatment contracts data in an Excel-based database that contains a list of all projects let by the Iowa DOT and Iowa cities or counties. Each record in the database contains information about the project such as project number, accounting number, project type, project length, and location referencing data. According to the project numbering policies and procedures released by the Iowa DOT Office of Finance, project numbers indicate the road system where the project is located, route number, milepost number, and county number. For example, the project number for a treatment applied on the interstate system starts with the letters IM, while the project number for a treatment applied on the primary system starts with NHS. The project type field indicates the treatment type applied. Some treatment types include the following:

- Crack seal
- Fog seal
- Slurry seal
- Seal coat
- HMA patch
- Portland cement concrete (PCC) patch
- Unbonded concrete overlay
- Bonded concrete overlay
- HMA resurfacing
- HMA resurfacing with milling
- HMA resurfacing with cold in-place recycling

Additionally, location referencing data were provided to describe the location of the project by using one or both of the following two systems:

- Linear referencing system (LRS)
- Geographic coordinate system (GCS)

The LRS uses a route number and beginning and ending mileposts to locate the starting and ending points for the project, and the GCS uses longitude and latitude data to locate a point along the project, which is the midpoint of the project. In the contracts database, the locations of the projects are described using GCS only, LRS only, or both systems.

Raw Pavement Condition Data

The raw pavement condition data is in a GIS-based database that contains distress data collected approximately every 32.8 feet (10 meters). It is worth mentioning that units of measurement have been changed to the English system since 2010 and distress data were collected every 52 feet. Additionally, the Iowa DOT collects pavement condition data every other year for half the network. For example, the pavement condition data for the northwest part of the state were collected in 2004, 2006, and 2008 while the pavement condition data for the southeast part of the state were collected in 2003, 2005, and 2007 (see Figure 2).

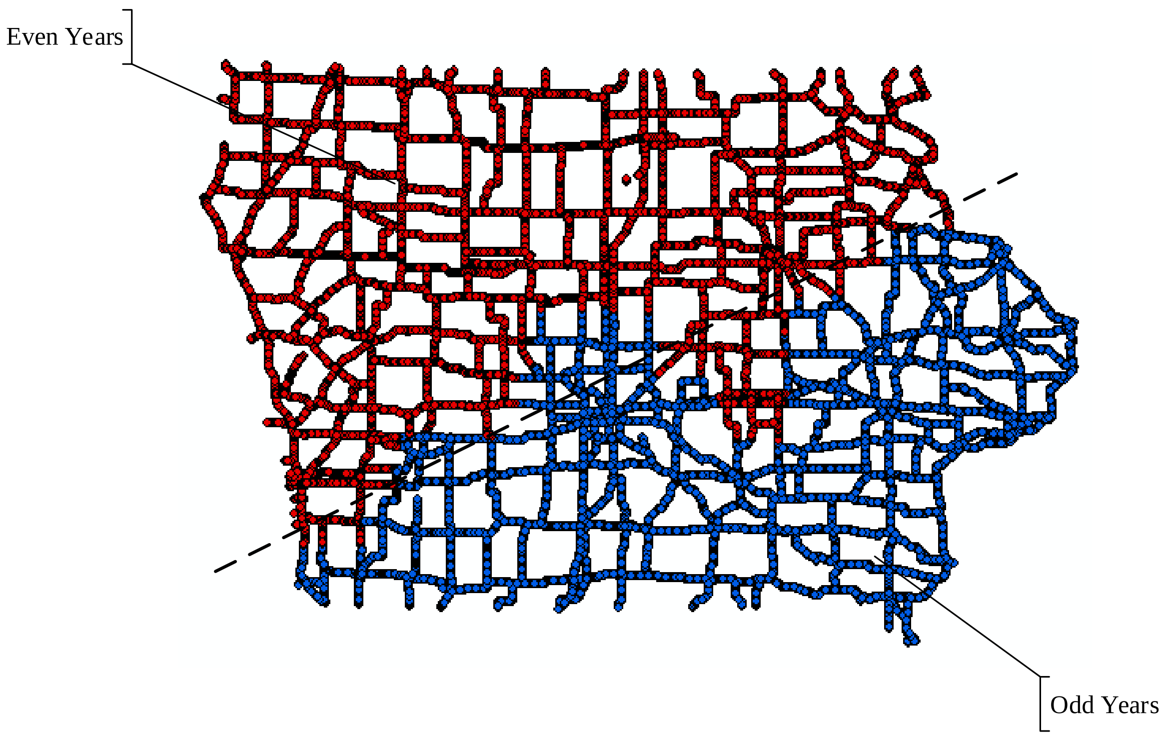

Figure 2. Pavement data collection practice in Iowa

After collecting the raw pavement condition data, the Iowa DOT applied a distress data aggregation process to produce data for the PMIS. This aggregation process involved averaging rut depth and IRI values to represent the condition of larger segments. For other distresses, such as transverse and longitudinal cracking, the number of cracks are aggregated to represent the length of cracks per unit length. In addition to the aggregated distresses, the PMIS contains traffic, material, and pavement history data, and so forth.

Selection of Treatment Types for Evaluation

The total number of projects let by the Iowa DOT and Iowa cities and counties from 1999 through 2007 (eight years) was approximately 2,187. The study focused on evaluating the performance of projects led by the Iowa DOT since the pavement condition data collected by them were coherent and available. Additionally, pavement condition data for Iowa city and county systems were not collected as frequently as the interstate and primary systems. As such, projects let by Iowa cities and counties were excluded. This brings the number of projects for this study to approximately 1,080, which are summarized by referencing system and treatment type in Table 2.

Table 2. Summary of treatment types

Treatment Type	GCS (Count)	LRS (Count)	Both Systems (Count)
PCC patch	184	90	274
HMA resurfacing	98	95	193
HMA joint-crack sealing	92	67	159
HMA crack filling	88	53	141
HMA resurfacing with milling	75	51	126
Slurry seal	32	26	58
HMA resurfacing with cold in-place recycling	22	3	25
Seal coat	2	18	20
PCC joint-crack filling	3	14	17
HMA patch	10	5	15
Microsurfacing	–	15	15
Transverse joint repair	12	1	13
PCC pavement replacement	5	5	10
PCC planing/grooving	4	1	5
Unbonded PCC overlay	3	1	4
Long joint repair	1	1	2
Fog seal	–	2	2
HMA pavement replacement	1	–	1

GCS = geographic coordinate system
LRS = linear referencing system

The study also focused on evaluating the improvement in pavement performance when a specific treatment was applied. As such, the study focused on evaluating the performance of rehabilitation treatments applied by the Iowa DOT:

- HMA resurfacing
- HMA resurfacing with milling
- HMA resurfacing with cold in-place recycling

The aforementioned treatments were found to be the most common rehabilitation treatments used by the Iowa DOT. Additionally, the evaluation of other maintenance/preservation treatments were not considered in this study since many of these projects were applied to off-system pavement projects or were not recorded in the PMIS. Moreover, performance improvement for pavements that received maintenance/preservation treatments could not be evaluated because of their data collection cycles.

On the other hand, localized treatments such as patching were not considered for evaluation because pavement distresses were aggregated to form longer segments with average/aggregated distress values and hence the evaluation of a localized treatment would yield misleading results unless the location of the treatment was accurately identified. The remaining maintenance and rehabilitation treatments were not considered for evaluation since there was not enough data points to draw sound conclusions.

Exclusions of Projects and Assumptions

It is worth noting that some projects were not considered for performance evaluation and were excluded for various reasons that will be discussed in the following subsections. With that mentioned, a summary of the number of segments and number of projects for each treatment type is provided in Table 3.

Table 3. Number of segments and projects analyzed

Treatment/Pavement Type	AC	PCC	Composite				Number of Projects
			JPCP*	CRC-CTB**	JRCP	CRC	
HMA resurfacing	5	51	26				37
CIPR	14		11				16
HMA resurfacing with milling	2		24	2	12	5	25

*AC layer over jointed plain concrete pavement (JPCP)
**AC layer over continuous reinforced concrete (CRC) with cement-treated base (CTB)

Long-Term Evaluation

This study mainly focused on evaluating the performance of rehabilitation treatments, and it is well established in the literature that rehabilitation treatments have long service lives. As such, projects applied in the period of 1999 to 2007 were considered for performance evaluation in order to evaluate their long-term performance. It is also worth noting that the last raw condition data available, at the time of conducting this study, was the 2013 raw condition data. Hence, the evaluation of projects constructed after 2007 only considered the short-term performance evaluation.

Missing Information for Treatment Thickness

Some of the rehabilitated segments considered for analysis did not have a treatment thickness change recorded in the PMIS. This was acceptable for HMA resurfacing with milling, however, there is definitely some sort of data entry error when it comes to HMA resurfacing and HMA resurfacing with CIPR. Moreover, those segments had clear performance improvements after treatment application. As such, treatment thickness was assumed to be similar to another segment based on traffic and pretreatment conditions.

Inconsistent Segment Lengths

The framework proposed uses a common ID assigned by the Iowa DOT to aggregate/average the raw condition data. The assigned ID was used to indicate that pavement sections share the same traffic volume, pavement materials, and maintenance history. However, in some cases, it was found that segments were divided into smaller segments and assigned a new ID, which hindered the distress aggregation process. For example, a pavement segment of 10 miles before treatment might be divided after treatment application into multiple segments. In such cases, the study ignored the PMIS segmentation information and aggregated the distress values to form one segment that covered the whole length of the project.

Inaccurate Distress Values

In some few cases, rutting or IRI values were too high or zeroed in a manner that indicated that there was an error in recording the pavement distress. In such cases, projects/records were excluded from the evaluation.

Pretreatment Condition Data

Many projects that were constructed during the three-year period of 2000 through 2003 did not have condition data recorded before treatment application. As such, these projects were excluded from the analysis.

Data Integration Technical Issues

The spatial integration process between the pavement treatment contracts data and the pavement condition data is the first step in evaluating the performance of different treatments. As the integration process was implemented, some technical difficulties occurred, which hindered the integration and performance evaluation processes. These technical difficulties are summarized in the following subsections.

Units of Measurement

The Iowa DOT used both the metric and English systems to record the pavement condition data and segment lengths. As for the raw pavement condition database, distress values and segment lengths were measured using the metric system until 2009. After 2010, the Iowa DOT collected data using the English system. On the other hand, for the pavement treatment contracts database, the lengths of projects were recorded in English units. As such, data were converted from English to metric units in order to unify the measurement units between the databases.

Pavement Condition Data Collection Issues

The Iowa DOT did not collect pavement condition data in 2010. Because of this, approximately half the network has a longer data collection gap. For example, a pavement segment with data collected in 2008 had proceeding condition data available in 2011 because the Iowa DOT collected the pavement condition data for the entire network in 2011. Additionally, the pavement condition data collected in 2002 was significantly geographically distorted since the condition data did not have the correct geographic coordinates. As a result, no spatial integration could be ascertained between pavement condition in 2002 and treatment projects.

Inaccurate Project Location Coordinates

The coordinates recorded in the database were used to spatially overlay project locations with the pavement condition data layer. The recorded longitudes and latitudes were supposed to be the midpoint of the pavement treatment project. However, some projects had inaccurate coordinates, thus manual editing of project locations was required to accurately overlay features. The manual editing was implemented by checking that the route number recorded matched the project number recorded in the PMIS.

Project Number Format and Mismatch

Project numbers are usually recorded in the PMIS in order to track pavement segment history. Additionally, changes in pavement thickness, surface material, and method of surface removal, if applicable, were recorded using the project number. However, the type of treatment applied was not recorded; this was the fundamental reason behind integrating the pavement treatment contracts database and the pavement condition data together. Since the project number was recorded in both the PMIS and the pavement treatment contracts database, it was logical to use it as a common attribute to merge or join the two databases together and associate the treatment type with the PMIS data. However, the merge process failed because of formatting and data entry issues for a majority of the projects. For example, an HMA resurfacing project was recorded in the pavement treatment contracts database with project number [STPN-044-4(39)--2J-39] while the same project was recorded in the PMIS as [STPN-44-4(39)--2J-39]. As such, spatial integration between the databases was implemented to overcome the data entry and formatting problems.

Using Raw Data versus PMIS

The Iowa DOT collects pavement condition data every 52 feet and then aggregates/averages the distress values based on the construction history of pavement to form homogenous pavement segments. Therefore, two sources of pavement condition data was used in this study:

- Raw condition data
- Aggregated condition data as stored in the PMIS

However, treatment projects do not necessarily cover the whole length of the PMIS segments and thus using the aggregated pavement condition data in some cases was misleading. Therefore, the raw condition data was used to evaluate the performance of treatments.

Project Letting and Construction Dates

In order to evaluate the performance of treatments, a construction date must be known to compare the pavement performance before and after treatment application. However, the letting dates of projects were the only dates recorded, and no construction or completion dates were recorded in the pavement treatment contracts database. Because of this issue, the study focused on major maintenance/rehabilitation projects that caused an observable significant pavement performance jump after treatment application. Therefore, the construction time of a project was determined by observing those immediate performance jumps.

ANALYSIS OF PAVEMENT TREATMENTS

Potential Performance Indicators

The Iowa DOT collects the following distress and condition data for pavement with asphalt concrete surfaces:

- Rut depth for left and right wheel paths
- Alligator cracking (moderate and high severity levels)
- Transverse cracking (low, moderate, and high severity levels)
- Longitudinal cracking (low, moderate, and high severity levels)
- Longitudinal cracking on wheelpath (low, moderate, and high severity levels)
- Number and area of patches (good and bad condition)
- IRI for left and right wheel paths

It is worth noting that all rehabilitation treatments evaluated in the study have an asphalt concrete surface. Therefore, distresses for pavement with asphalt concrete surfaces were considered as potential performance indicators.

It was well established from the literature review that the service life of different treatments will change based on the performance indicator used. As such, an accurate and reliable treatment performance evaluation should consider using different performance indicators for the evaluation process. Based on that, the performance of different segments were investigated based on individual distress data collected by the Iowa DOT.

Segments Classification

The segments analyzed were categorized into four groups based on the average annual ESAL. The classification of segments by traffic loadings was conducted to compare the performance of the same treatment subjected to similar traffic loadings. Figure 3 shows a histogram for the number of segments based on the ESALs for HMA resurfacing applied to composite pavements.

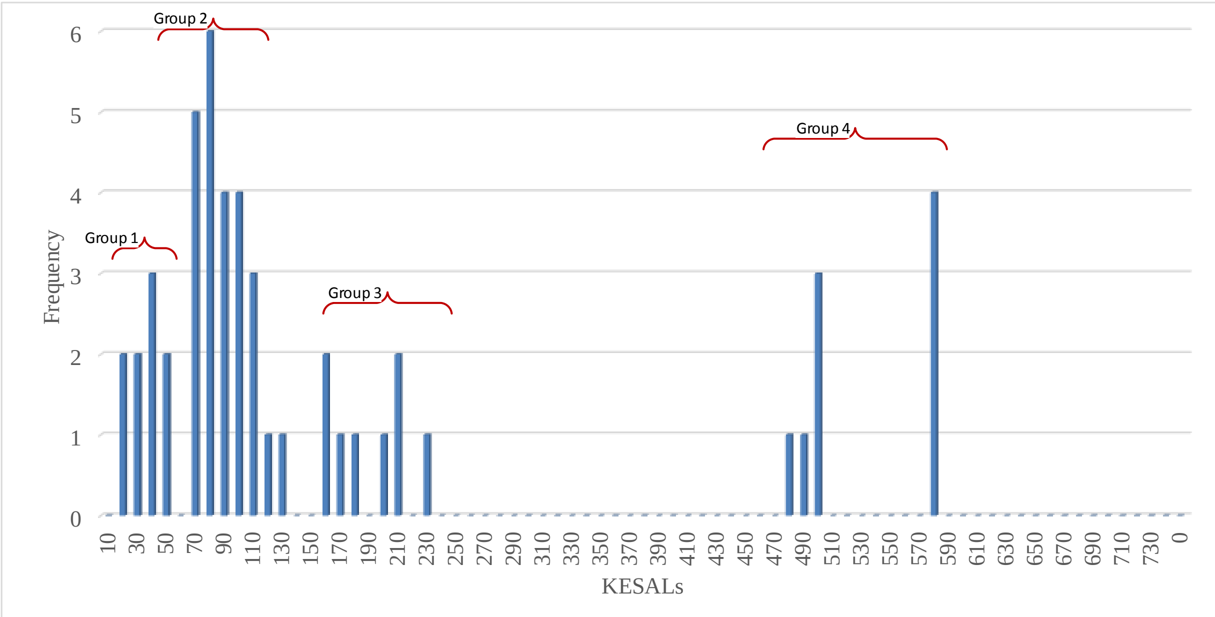

Figure 3. Classification of segments analyzed for HMA resurfacing on PCC pavements

The segments are grouped as follows:

- Segments with ESALs less than 70,000 (Group 1)
- Segments with ESALs greater than 70,001 and less than 130,000 (Group 2)
- Segments with ESALs greater than 130,001 and less than 250,000 (Group 3)
- Segments with ESALs greater than 250,001 (Group 4)

The aforementioned breaks were found to be common between the different treatment types. As such, the same breaks were used to classify segments for other treatments. Afterward, each segment was studied individually to analyze the deterioration pattern for each distress.

In the following subsections, the analysis of treatment performance applied to different types of pavements is presented. First, the performance of PCC pavements after the application of HMA resurfacing is analyzed. Afterward, the performance of composite pavement with JPCP after applying HMA resurfacing, HMA resurfacing with milling, and HMA resurfacing with CIPR is presented. Similarly, the performance of composite pavement with JRCP after receiving HMA resurfacing with milling is analyzed. Finally, performance of asphalt concrete pavement after receiving HMA resurfacing with CIPR is presented.

The evaluation of performance in terms of different distresses is based on the severity and extent levels that were previously identified and used for pavement treatment selection purposes for Iowa local agencies (Abdelaty et al. 2015). Table 4 shows the extent and severity levels for AC pavement surfaces.

Table 4. AC distress severity and extent levels

Distress	Severity Level	Severity Level Threshold Values	Extent Level	Extent Level Threshold Values
Alligator Cracking	Low	Few connecting cracks	Low	1–9% of wheel path affected
	Moderate	Interconnected cracks forming pattern	Moderate	10–24% of wheel path affected
	High	Severely interconnected cracks	High	More than 25% of wheel path affected
Longitudinal Cracking	Low	Mean width less than 0.25 in. (6 mm)	Low	Less than 2,640 ft/mile (500 m/km)
	Moderate	Mean width greater than or equal to 0.25 in. (6 mm) and less than 0.75 in. (19 mm)	Moderate	From 2,640 ft/mile (500 m/km) to 5,279 ft/mile (999 m/km)
	High	Mean width greater than or equal to 0.75 in.(19 mm)	High	Greater than or equal 5,280 ft/mile (1000 m/km)
Transverse Cracking	Low	Mean width less than 0.25 in.(6 mm)	Low	Less than 792 ft/mile (150 m/km)
	Moderate	Mean width greater than or equal to 0.25 in.(6 mm) and less than 0.75 in.(19 mm)	Moderate	From 792 ft/mile (150 m/km) to 1,584 ft/mile (300 m/km)
	High	Mean width greater than or equal to 0.75 in.(19 mm)	High	Greater than or equal 1,584 ft/mile (300 m/km)
Rutting	Low	Mean depth less than 0.27 in (7 mm)	Low	1–9% of wheel path affected
	Moderate	Mean depth greater than or equal to 0.27 in.(7 mm) and less than 0.5 in.(12 mm)	Moderate	10–24% of wheel path affected
	High	Mean depth greater than or equal to 0.5 in.(12 mm)	High	More than 25% of wheel path affected

Abdelaty et al. 2015

PCC Pavements

PCC pavements are also known as rigid pavements that have been mainly maintained using HMA resurfacing. The performance of HMA resurfacing is analyzed in the following subsection.

HMA Resurfacing

The average pavement thicknesses after overlay were 11.77, 13.62, 14.48, and 12.99 in (299, 346, 368, and 330 mm) while the average overlay thicknesses were 3.38, 4.05, 4.44, and 3.6 in

(86, 103, 113, and 92 mm) for Groups 1 through 4, respectively. The average thickness of the pavement and overlays increased as traffic loadings were increased, except for Group 4. The analysis of individual distress deterioration is presented in the next subsection.

As for the distress deterioration figures in the next subsections, it was found that including the deterioration patterns for all segments in one figure would be confusing. As such, test segments were divided into subgroups based on extent level of distress before treatment application. This is also beneficial because one can visually interpret the relationship between the pretreatment condition and distress propagation over time. Each figure is titled with a group number, which indicates the level of traffic loadings. Additionally, segments in each group were alphabetically numbered so readers can track the performance of specific segment in terms of other distresses.

Alligator Cracking

The performance of segments was analyzed in terms of moderate and high severity levels. As for moderate severity cracks, most of the segments analyzed had almost zero m^2/km alligator cracks before treatment application. Figure 4 shows moderate alligator cracking deterioration over time for different segments.

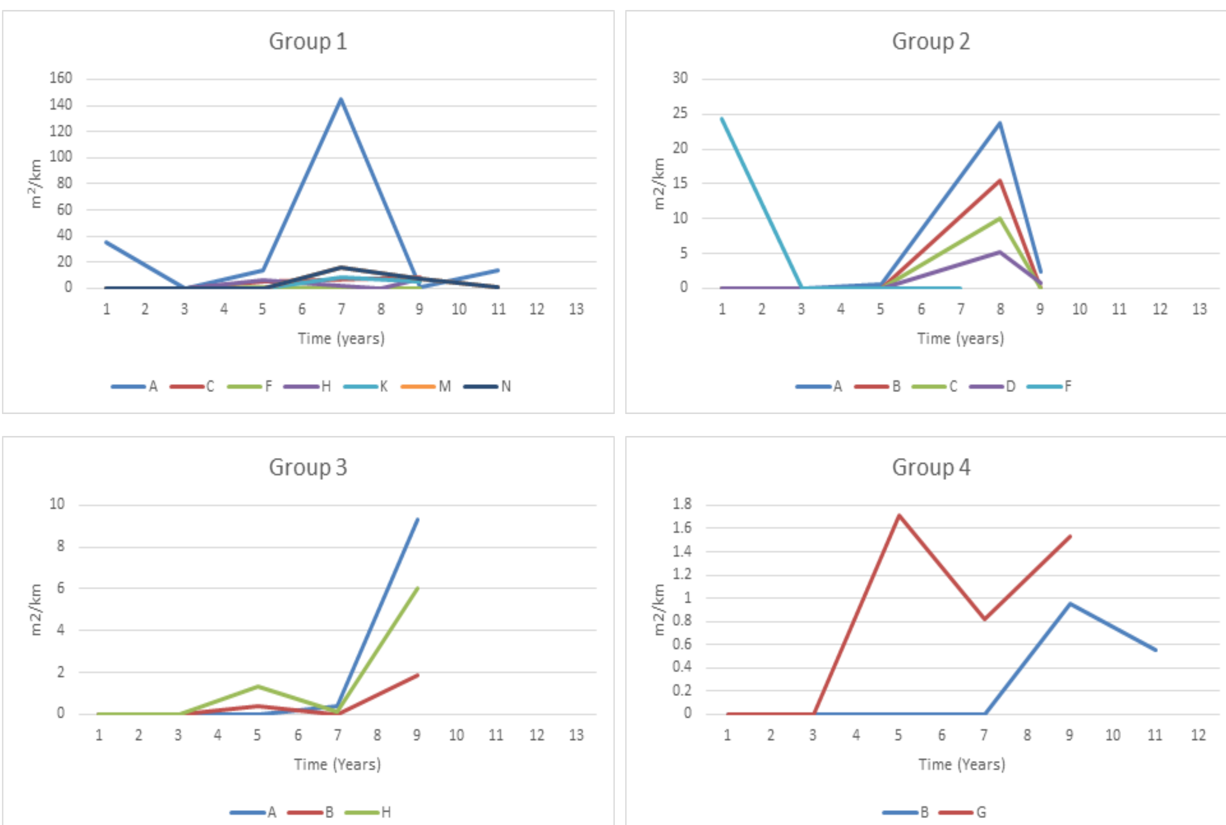

Figure 4. Moderate alligator cracking deterioration for Groups 1, 2, 3, and 4

It was found that the deterioration of alligator cracking had unexpected sudden improvements after treatment application. For instance, Segment A in Group 1 had a moderate alligator crack area decrease after year five and seven, respectively (see Figure 4). Since the high alligator cracks for the same segment remained almost zero at all times, it was expected that this decrease would correspond to an increase in the patched area of this specific segment. However, no increase in the patched area was recorded that corresponded to the decrease in moderate alligator cracks. A second possible scenario included assuming that other maintenance or rehabilitation treatments were applied. However, there were no maintenance or rehabilitation projects recorded in the PMIS. Additionally, no improvement, in terms of road roughness, was observed for the same segment between year seven and nine (as shown later in Figures 26 and 28). It was quite reasonable to assume that unrecorded in-house maintenance was applied to address the moderate alligator cracks.

On the other hand, some segments had a decrease in alligator cracking area that corresponded to an increase in the patched area in the same section. For instance, Segment N in Group 1 (see Figure 4) had a decrease in alligator cracking area after year eight. In the same year, the patched area per unit length increased.

It is worth mentioning that many segments had zero or almost zero m^2/km alligator cracks and hence were not included in the graphs. Similarly, all segments had zero or almost zero m^2/km high severity alligator cracks.

Transverse Cracks

Similarly, the performance of pavement segments for all distress levels was analyzed. Figures 5 and 6 show the deterioration of low transverse cracking over time.

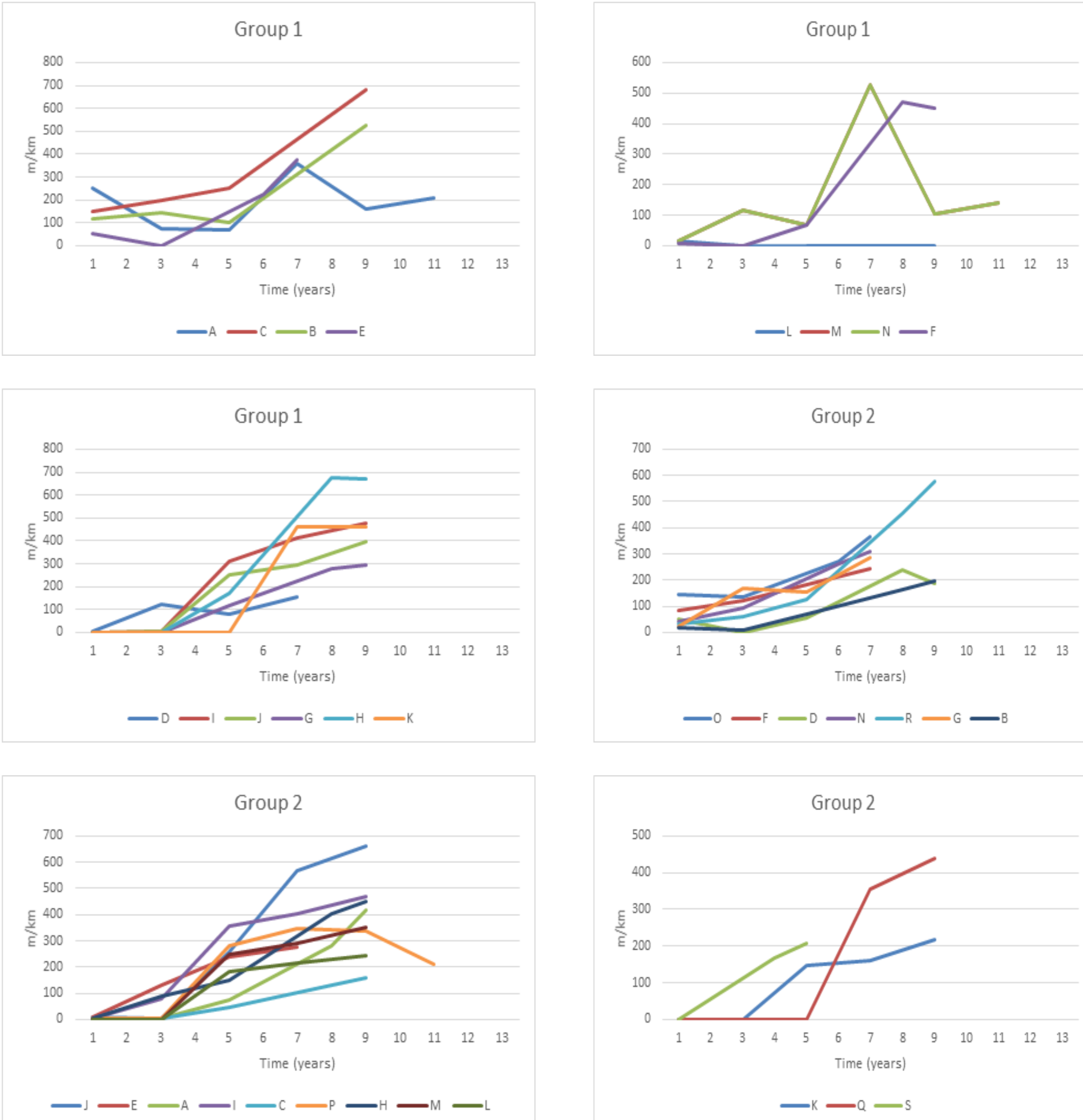

Figure 5. Low transverse cracking deterioration for Groups 1 and 2

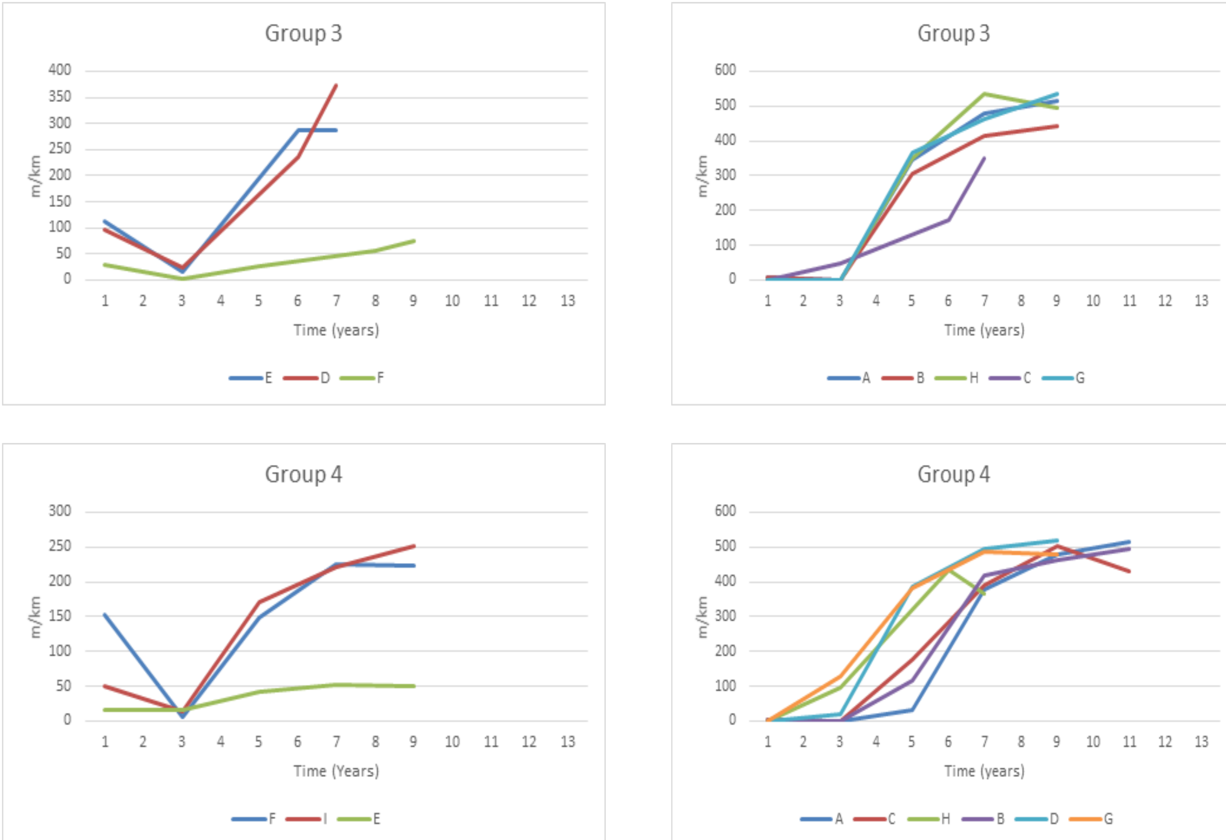

Figure 6. Low transverse cracking deterioration for Groups 3 and 4

In terms of distress propagation, it was observed that the majority of segments analyzed did not exhibit short-term performance jumps in terms of low transverse cracks (see Figures 5 and 7).

Figure 7. Moderate transverse cracking deterioration for Groups 1 and 2

Additionally, transverse cracks might be reflected into the new surface and hence affect the short-term performance. Moreover, normal pavement deterioration process will increase the rate of transverse crack propagation. In terms of long-term performance, it was observed that low transverse cracks increased drastically when compared to the pretreatment condition. A possible reason for that trend was that sealed transverse cracks were recorded as low transverse cracks. As for moderate and high severity transverse cracks, short-term performance jumps were observed for many segments. However, there was no regular pattern in long-term performance, as the extent of moderate and high severity cracks for many segments had abrupt performance jumps (see Figures 7 through 10).

Similarly, moderate transverse cracks propagation was monitored over time. Figures 7 and 9 show the deterioration pattern for moderate severity transverse cracks. It was observed that most segments showed a decrease in the amount of transverse cracking after treatment application. However, the performance of segments on the long term was irregular because of the existence of sudden unexpected improvements.

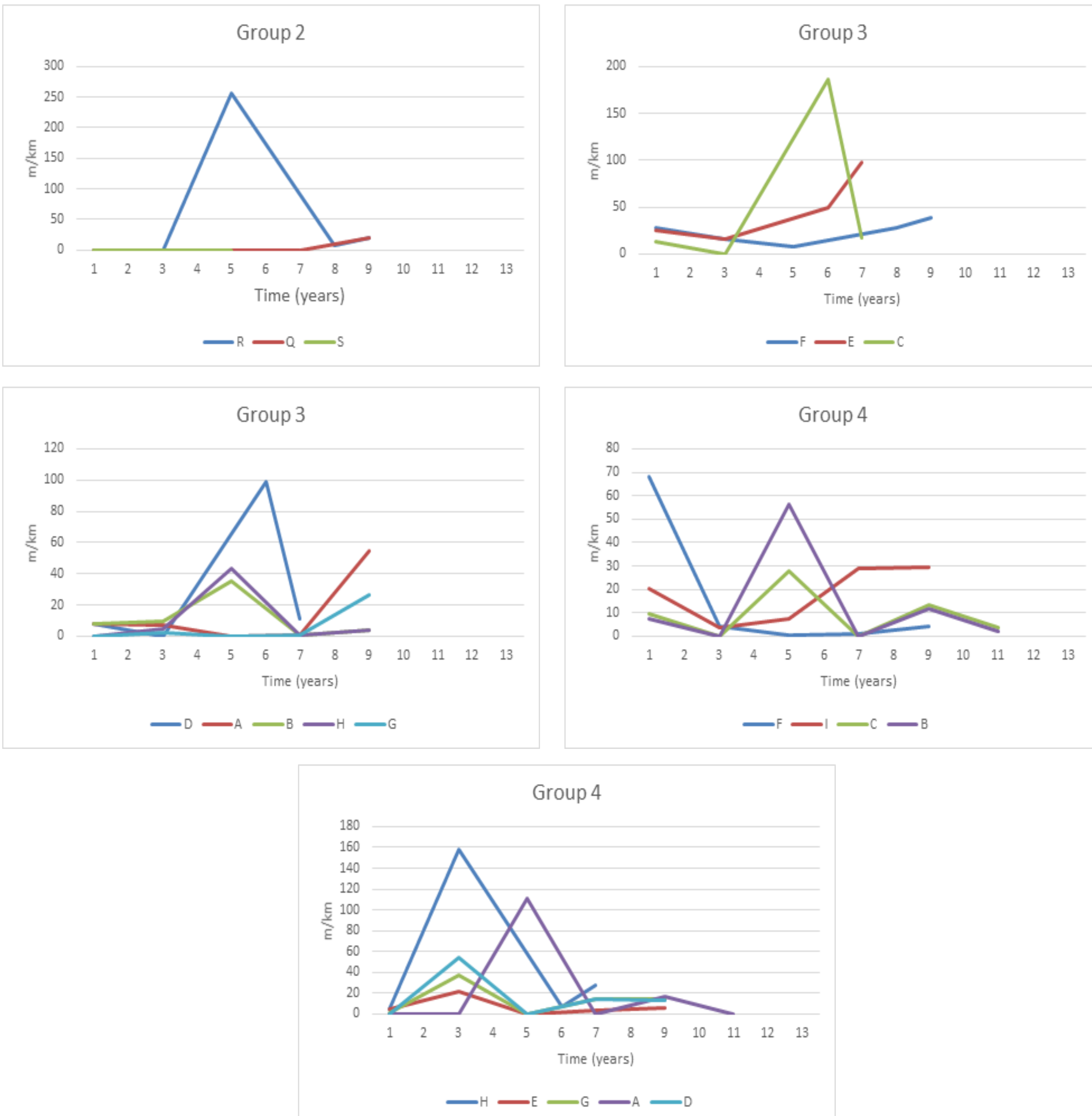

Figure 8. Moderate transverse cracking deterioration for Groups 2, 3, and 4

Similarly, the propagation of high severity transverse cracks was monitored over time. Figures 9 and 10 show the deterioration pattern for high severity transverse cracks. A reduction in the transverse cracking amount was observed after treatment application. However, segments did not have a regular long-term performance pattern because of the sudden performance jumps. It is also worth noting that the majority of segments exhibited good performance since the level of extent did not exceed 50 m/km.

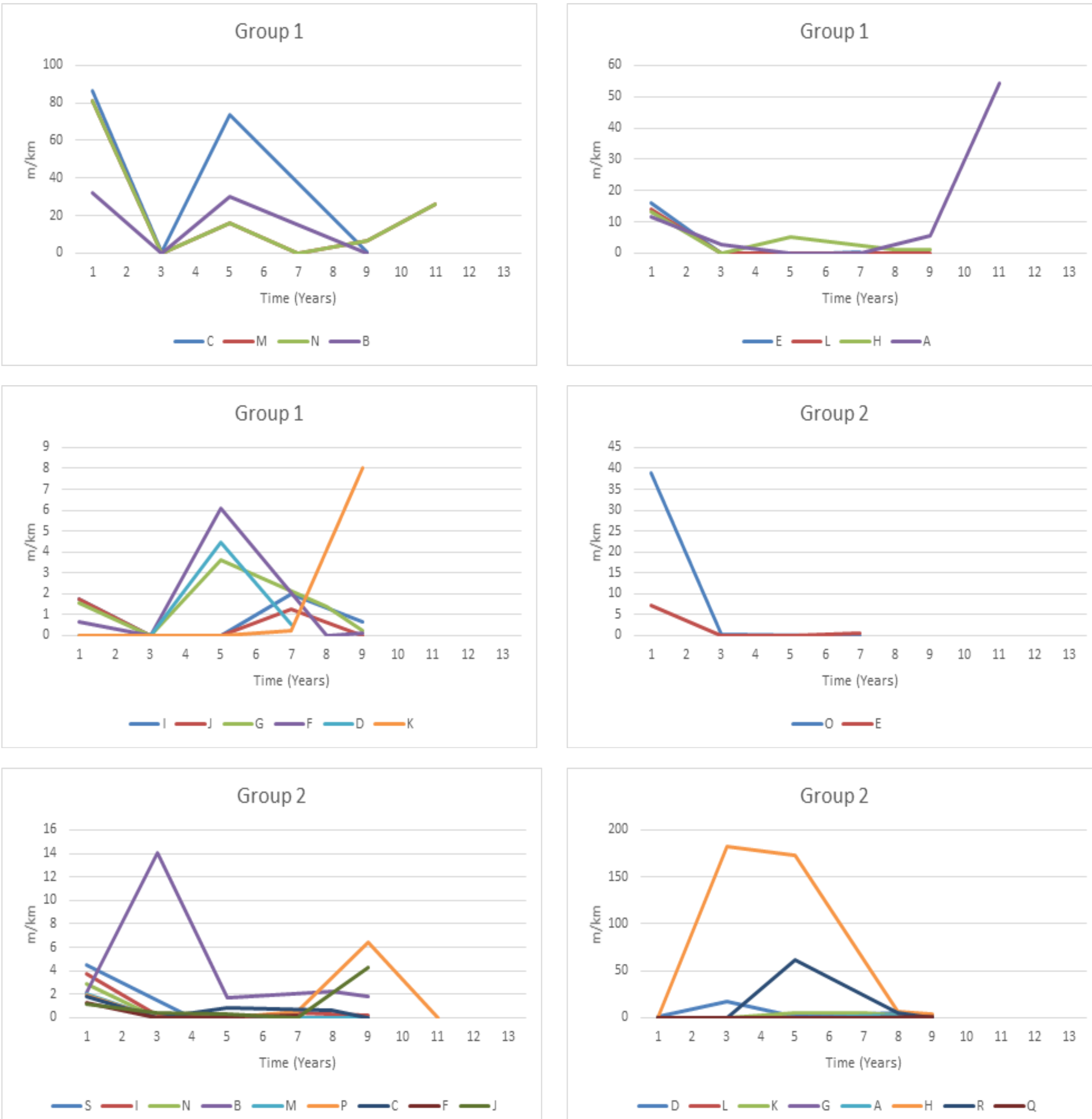

Figure 9. High transverse cracking deterioration for Groups 1 and 2

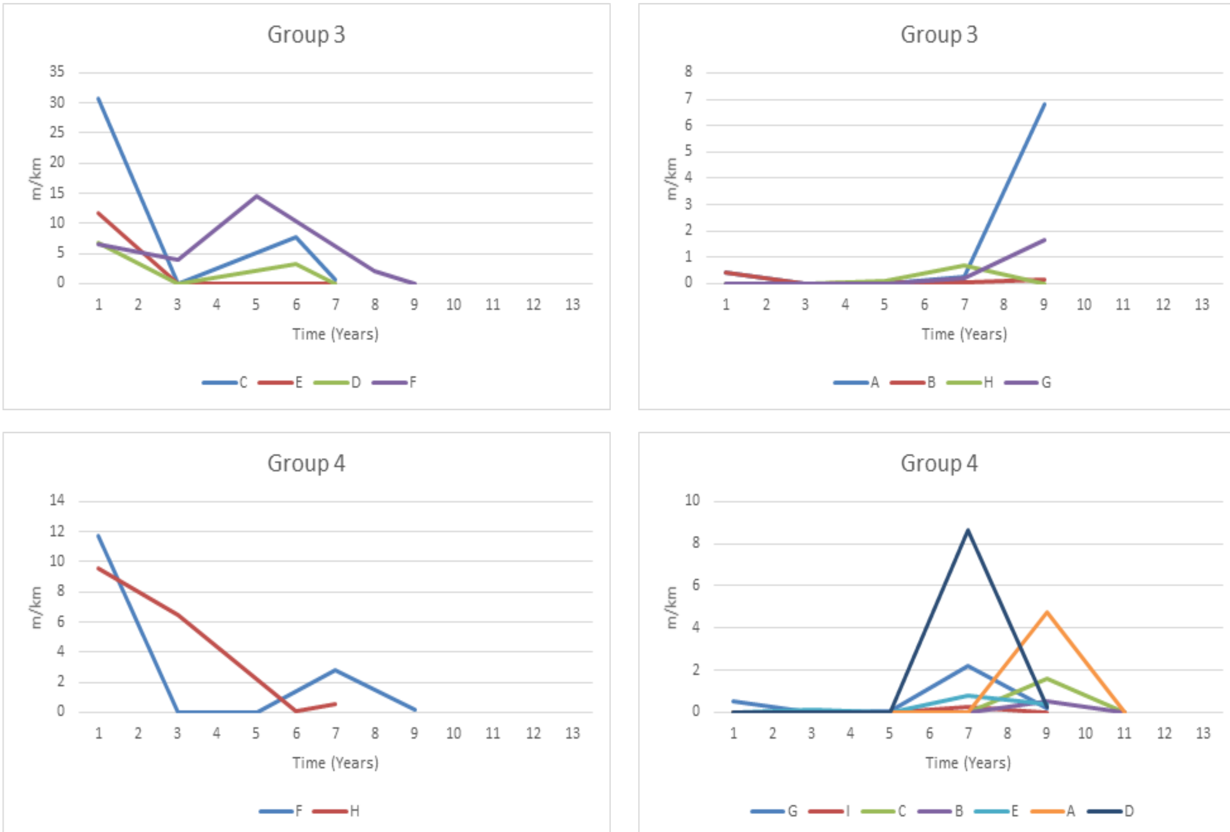

Figure 10. High transverse cracking deterioration for Groups 3 and 4

Longitudinal Cracking

The performance of pavements, in terms of longitudinal cracking propagation, was monitored before and after treatment application for each severity level. Figures 11 and 12 show the deterioration of low severity longitudinal cracks.

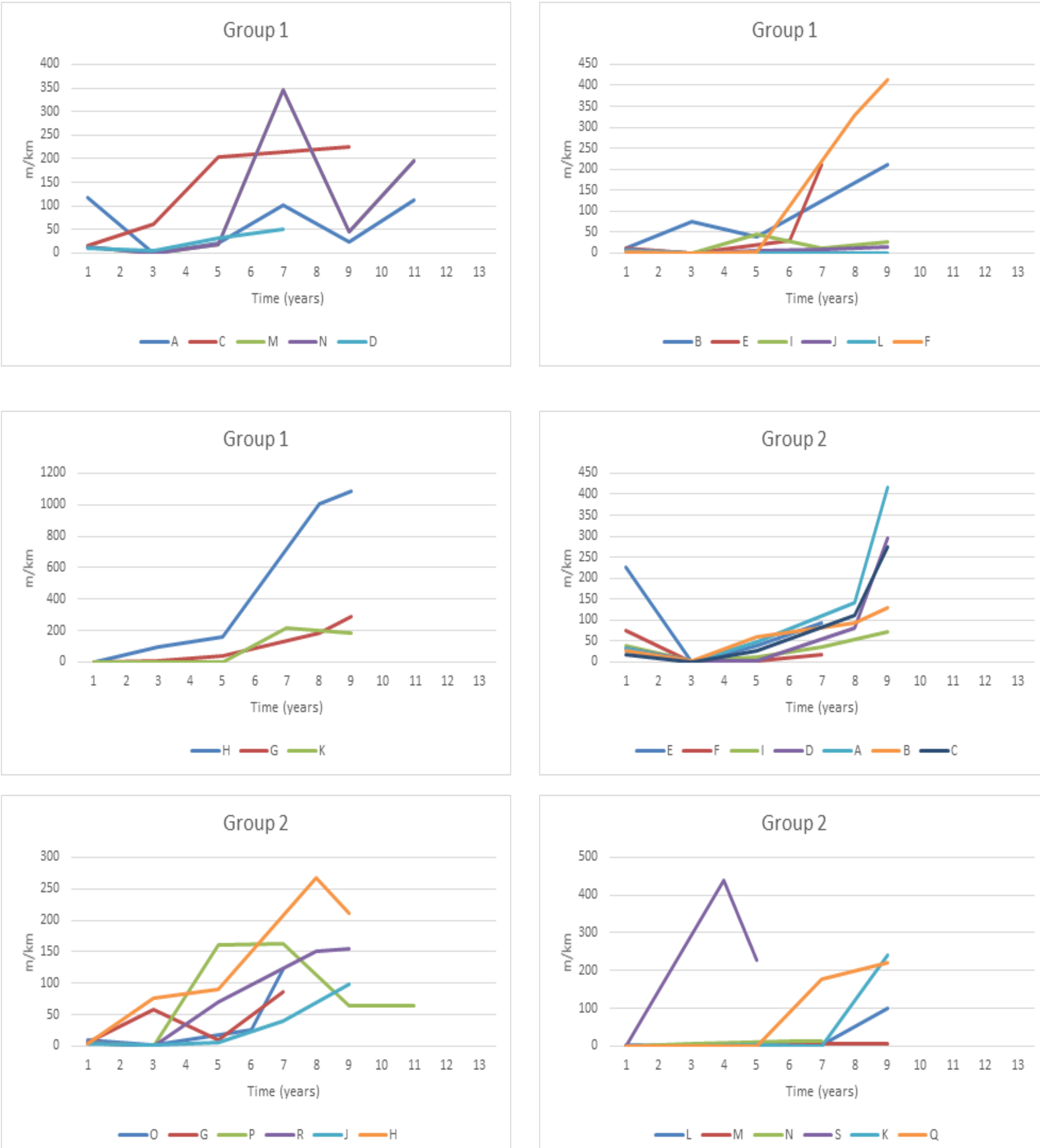

Figure 11. Low longitudinal cracking deterioration for Groups 1 and 2

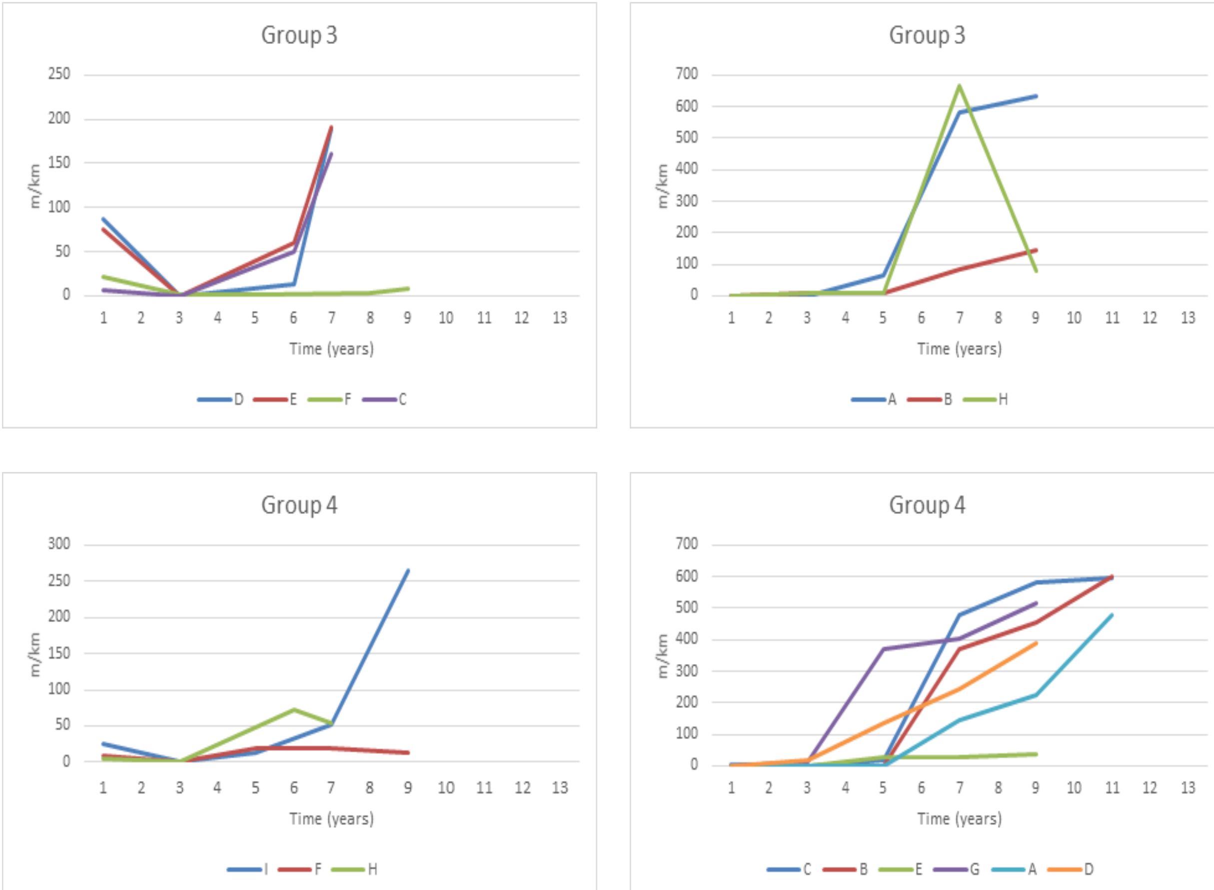

Figure 12. Low longitudinal cracking deterioration for Groups 3 and 4

Longitudinal cracks had a similar deterioration issue when compared with the deterioration of transverse cracking. However, short-term performance jumps for many segments were observed in terms of low severity longitudinal cracks. Also, it was observed that the rate of low severity longitudinal crack propagation significantly increased after five years of treatment application for Group 2 (see Figure 11) and three years for Group 3 (see Figure 12).

Similarly, moderate severity longitudinal cracks propagation was monitored over time. Figures 13 and 14 show the deterioration pattern for moderate severity longitudinal cracks. It was observed that the majority of segments analyzed had a relatively low extent level of moderate severity longitudinal cracks. However, a clear immediate performance jump and irregular long-term deterioration patterns were observed.

Figure 13. Moderate longitudinal cracking deterioration for Groups 1 and 2

Figure 14. Moderate longitudinal cracking deterioration for Groups 3 and 4

Figures 15 and 16 show the deterioration pattern for high severity longitudinal cracks. It was found that immediate improvements were observed after treatment application. It was also observed that segments had exhibited long-term good performance since they had a relatively low level of extent.

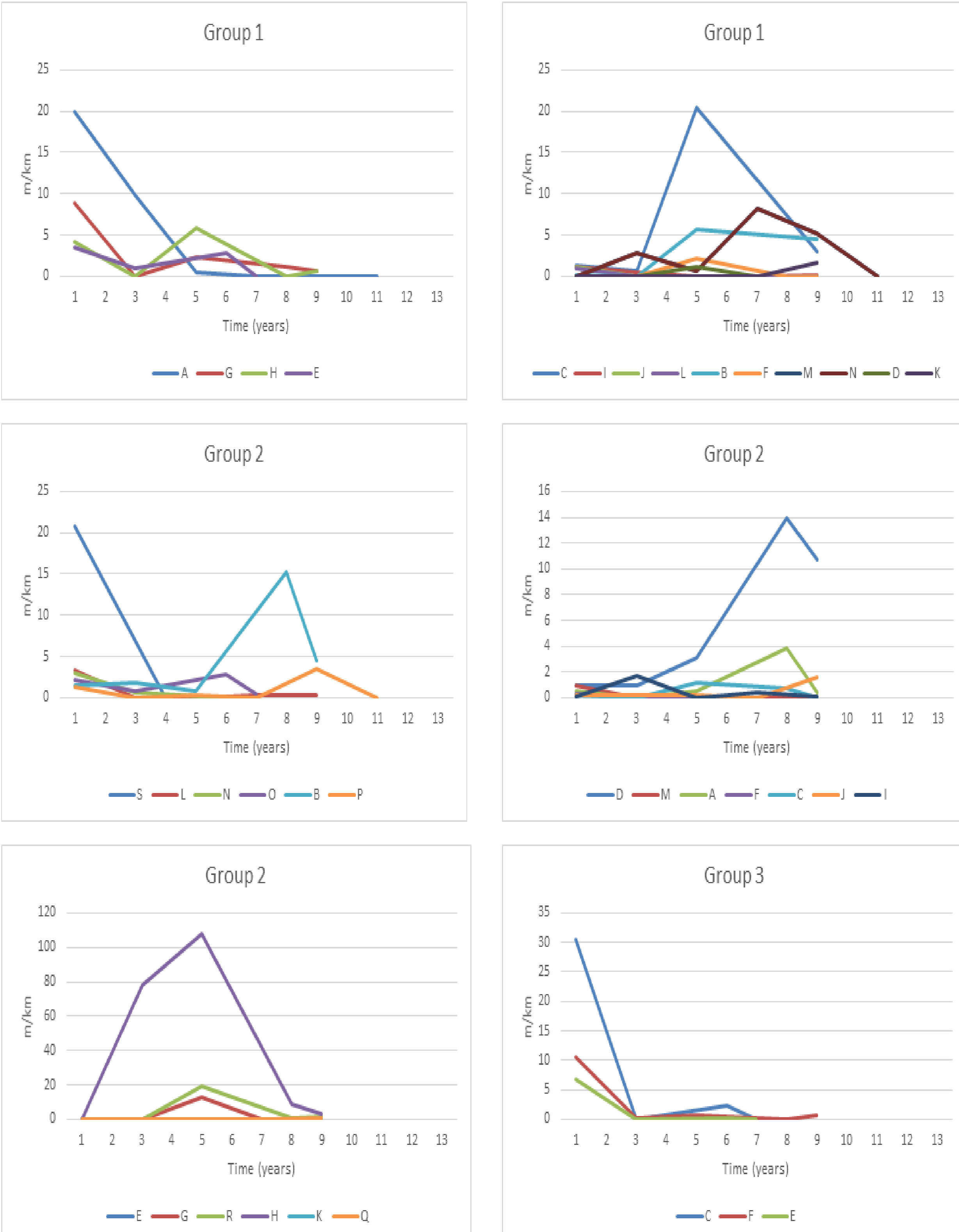

Figure 15. High longitudinal cracking deterioration for Groups 1, 2, and 3

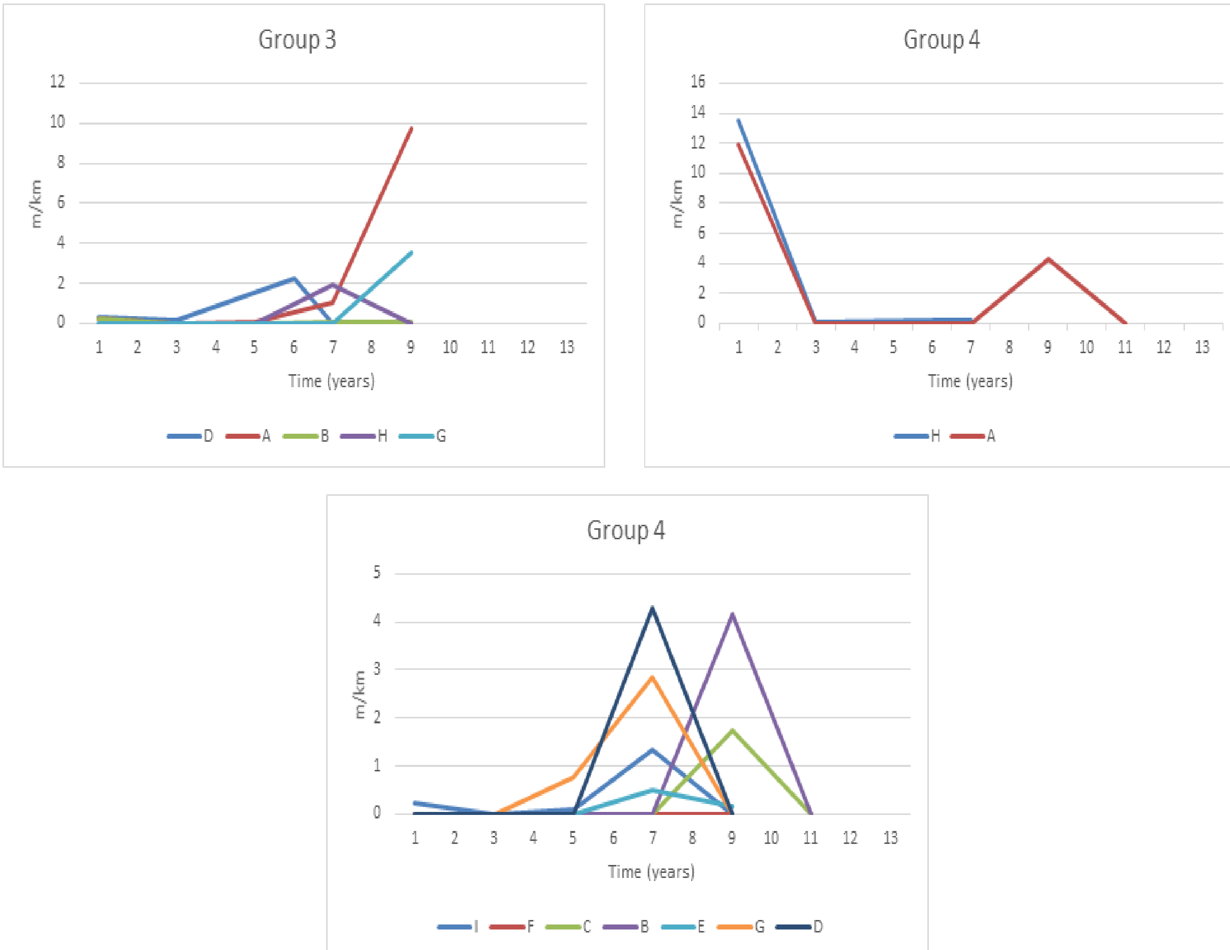

Figure 16. High longitudinal cracking deterioration for Groups 3 and 4

Longitudinal Cracking on Wheelpath

The performance of pavements, in terms of longitudinal cracking on wheelpath propagation, was also monitored before and after treatment application for each severity level. Figures 17 and 18 show the deterioration of low severity longitudinal cracks on the wheelpath.

Figure 17. Low longitudinal cracking deterioration on wheelpath for Groups 1 and 2

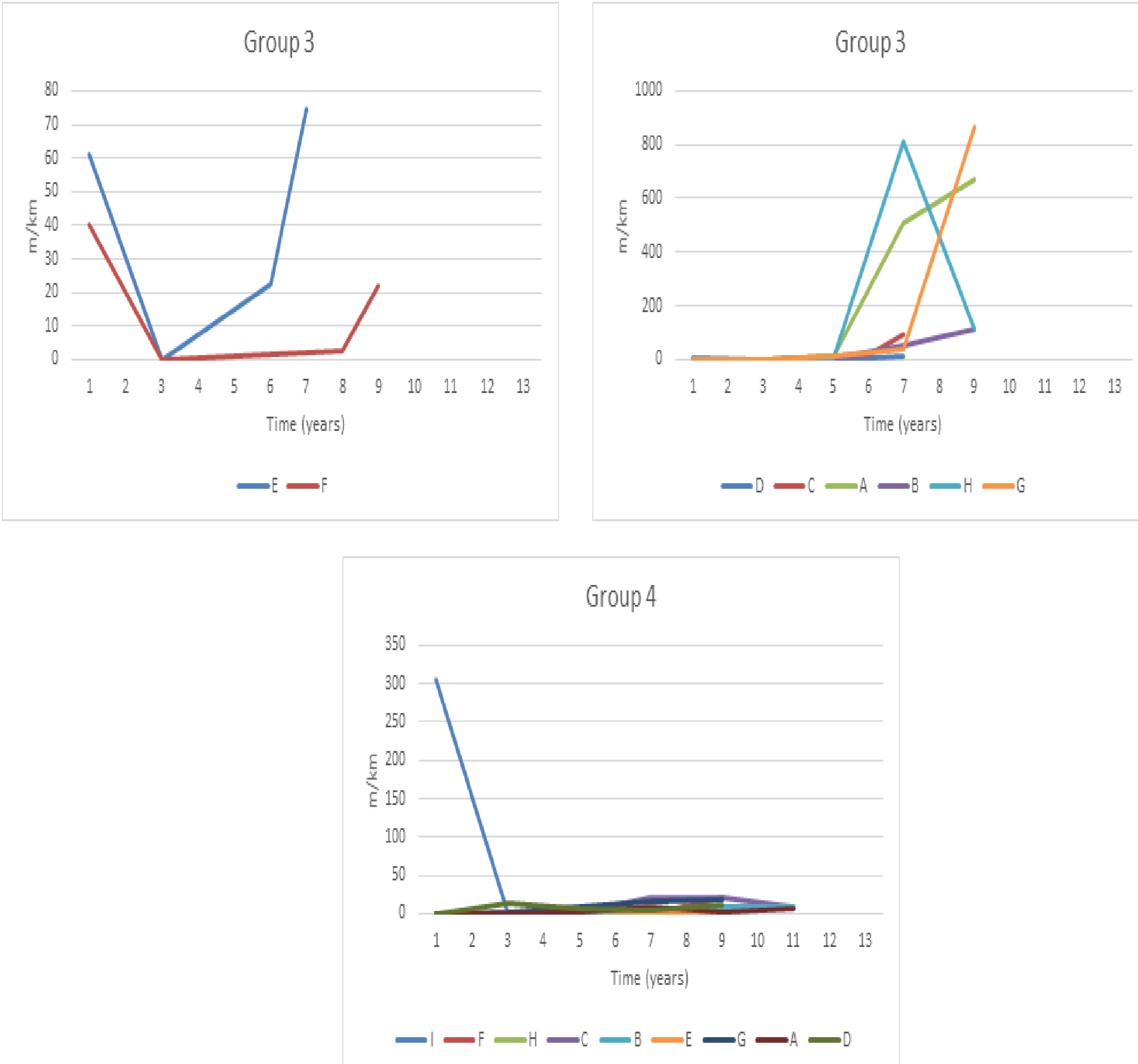

Figure 18. Low longitudinal cracking deterioration on wheelpath for Groups 3 and 4

As for low severity longitudinal cracks on the wheelpath, few segments had abrupt performance jumps after treatment application. However, the deterioration pattern was closely linked with the alligator cracking deterioration pattern. For instance, Segment A in Group 1 had significant performance increases in terms of longitudinal cracking on the wheelpath and alligator cracks (see Figures 4 and 17). On the other hand, Segments A, B, C, and D in Group 2 had significant decreases in alligator cracking and significant increases in longitudinal cracking on the wheelpath.

Similarly, moderate severity longitudinal cracking propagation was monitored over time. Figures 19 and 20 show the deterioration pattern for moderate severity longitudinal cracks on the wheelpath. Observations regarding the long-term and short-term performance are very similar to the previous distresses.

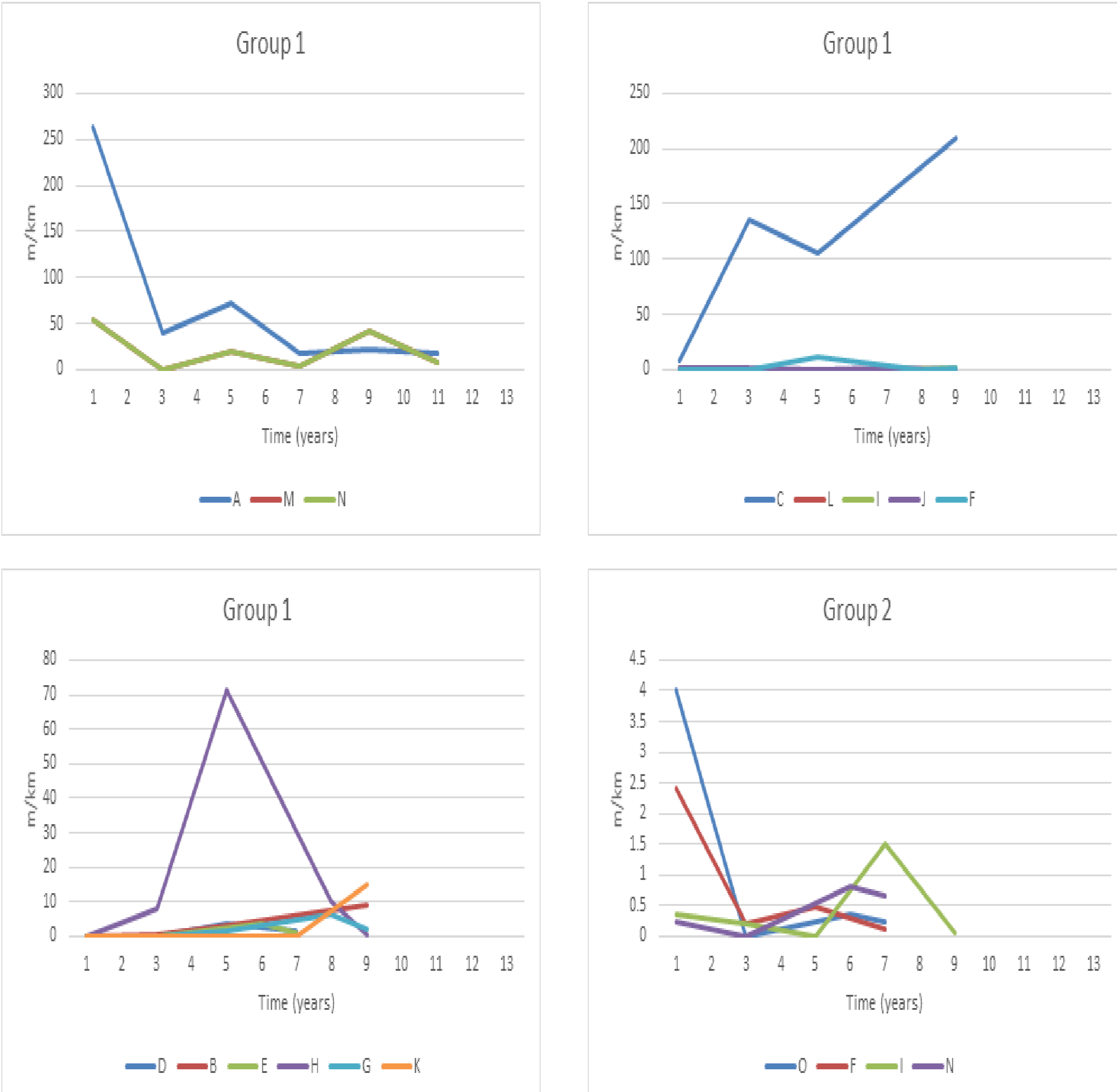

Figure 19. Moderate longitudinal cracking deterioration on wheelpath for Groups 1 and 2

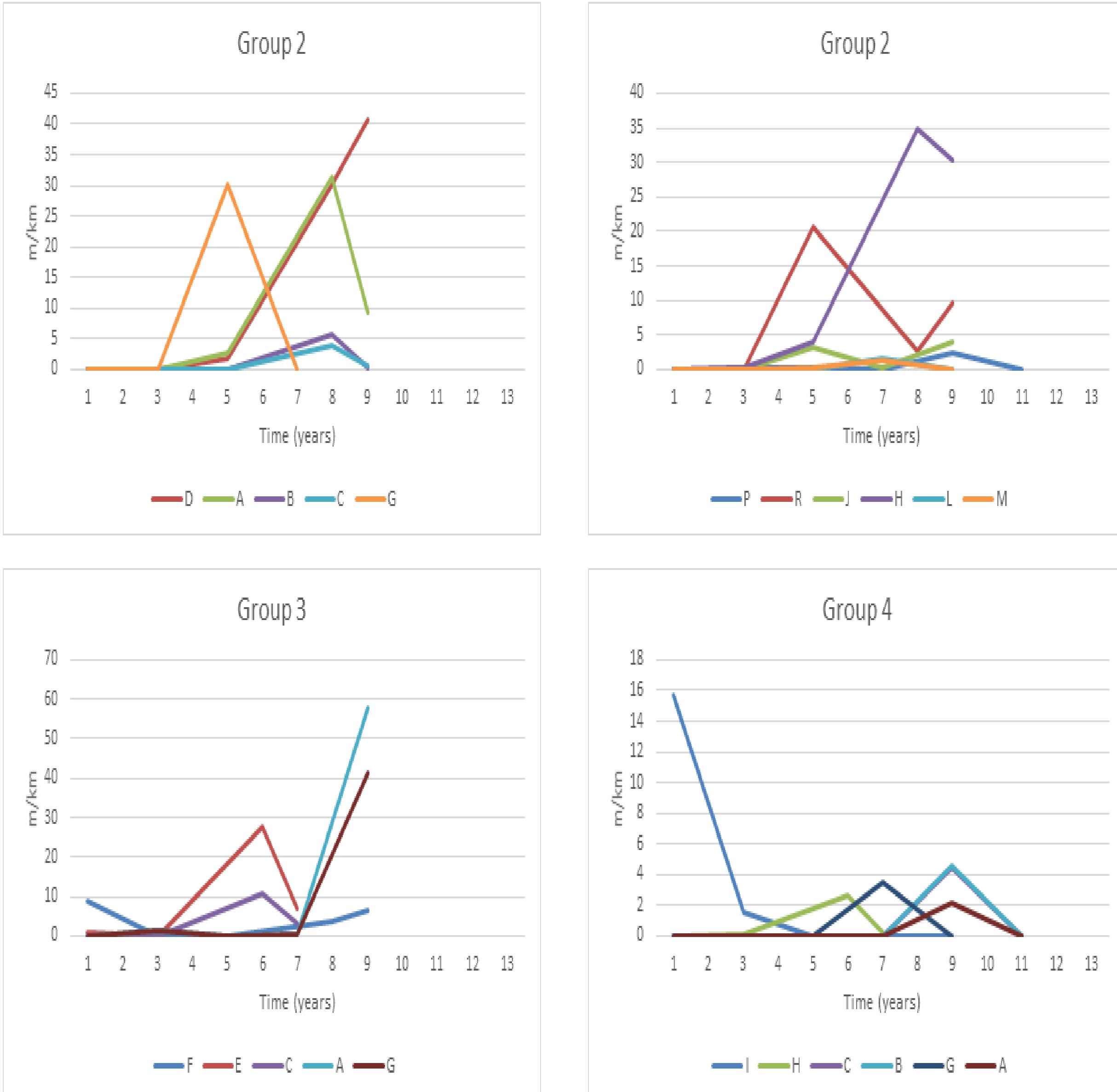

Figure 20. Moderate longitudinal cracking deterioration on wheelpath for Groups 2, 3, and 4

Similarly, high severity longitudinal cracks on the wheelpath propagation was monitored over time. Figures 21 and 22 show the deterioration pattern for high severity longitudinal cracks on the wheelpath. It is worth mentioning that the majority of the segments had zero or almost zero m/km and hence were not included in Figures 21 and 22.

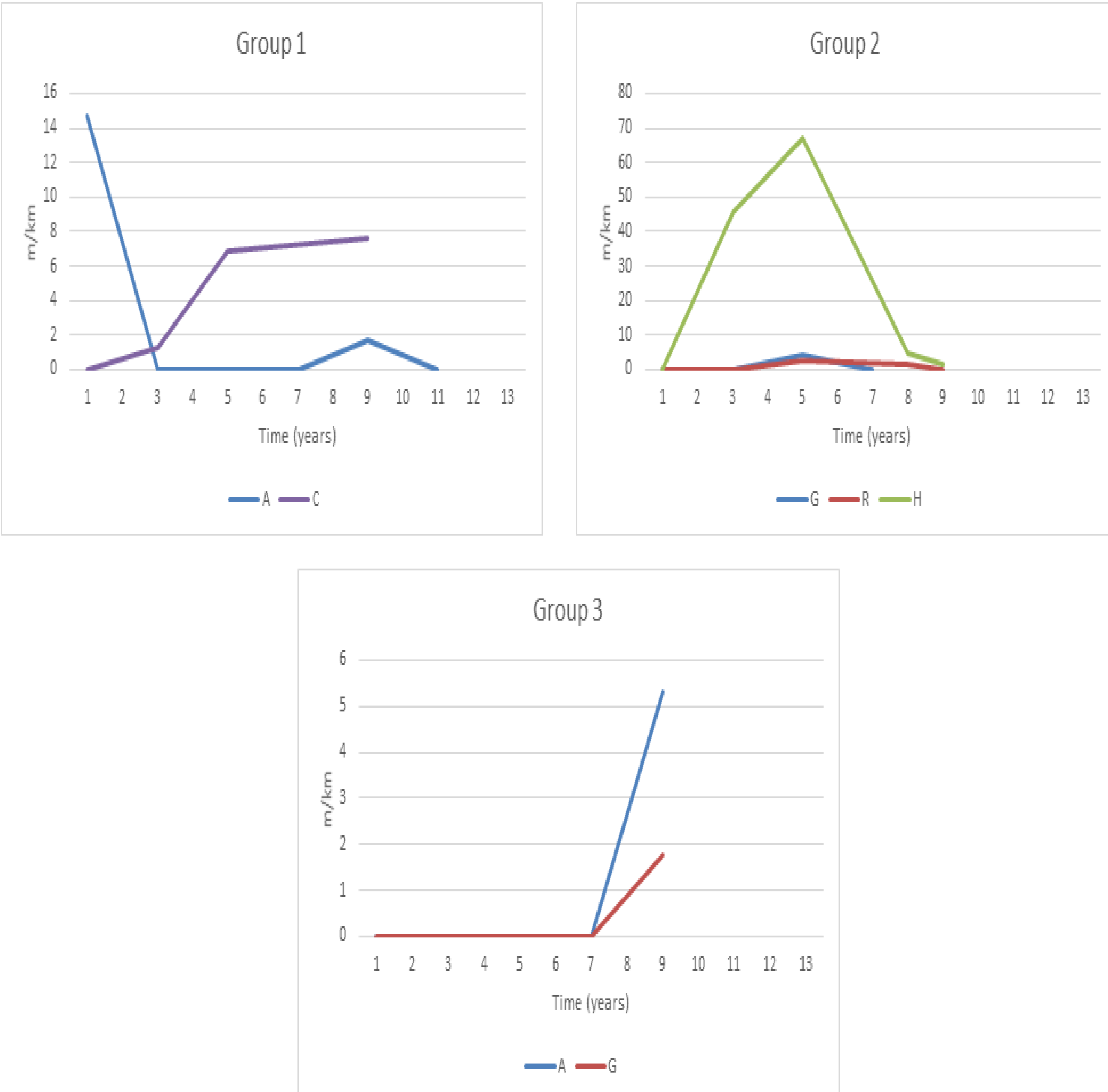

Figure 21. High longitudinal cracking deterioration on wheelpath for Groups 1, 2, and 3

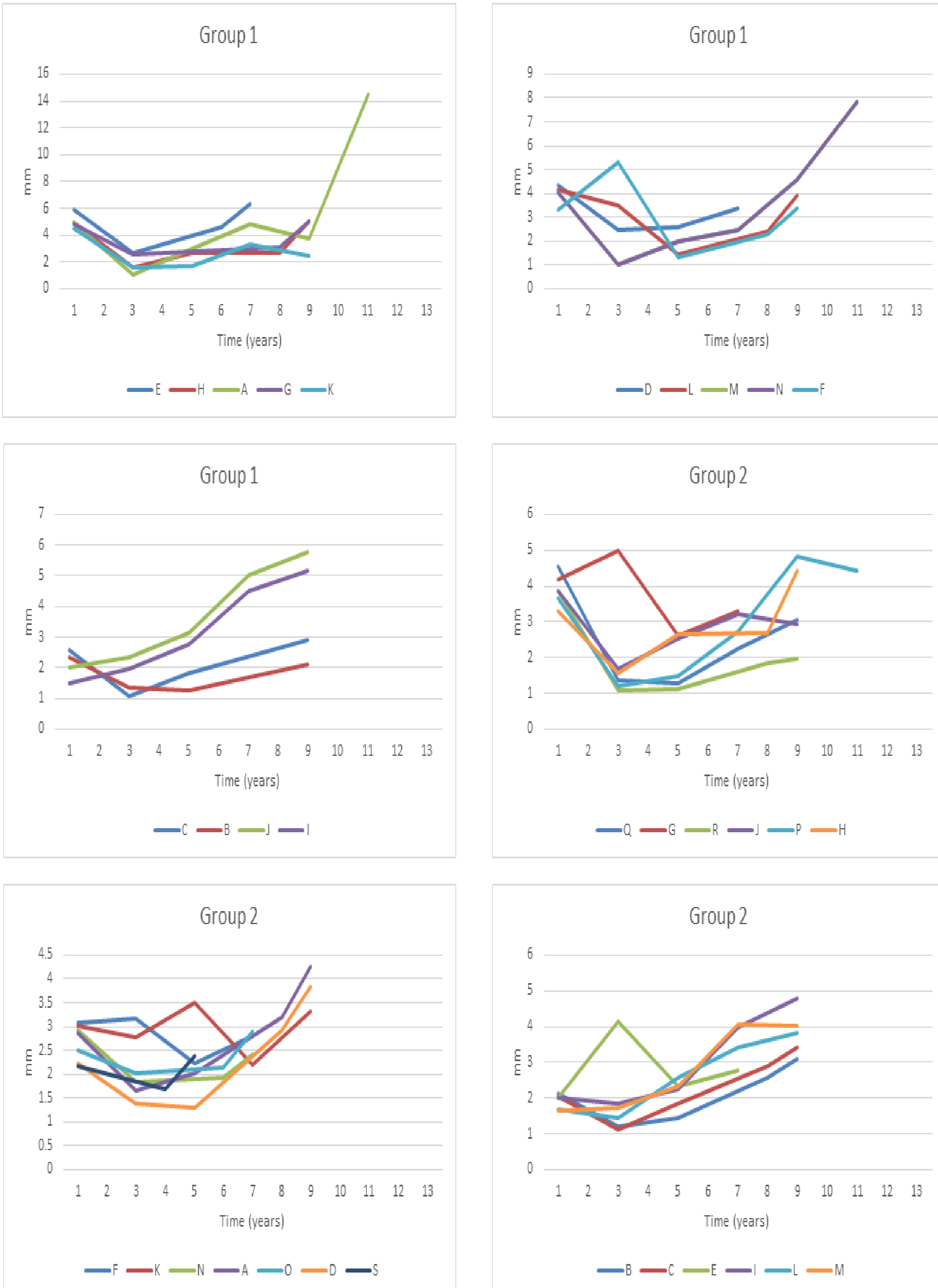

Figure 22. Rut depth for right wheelpath deterioration for Groups 1 and 2

Rutting

Similarly, rutting rate of deterioration for both left and right wheelpaths were monitored before and after treatment application. Figures 22 through 25 show the rate of deterioration for rutting. It was observed that fewer segments had inconsistent performance patterns when compared to the other previous distresses. Additionally, the majority of the segments analyzed had a clear performance jump immediately after treatment application and regular deterioration over time.

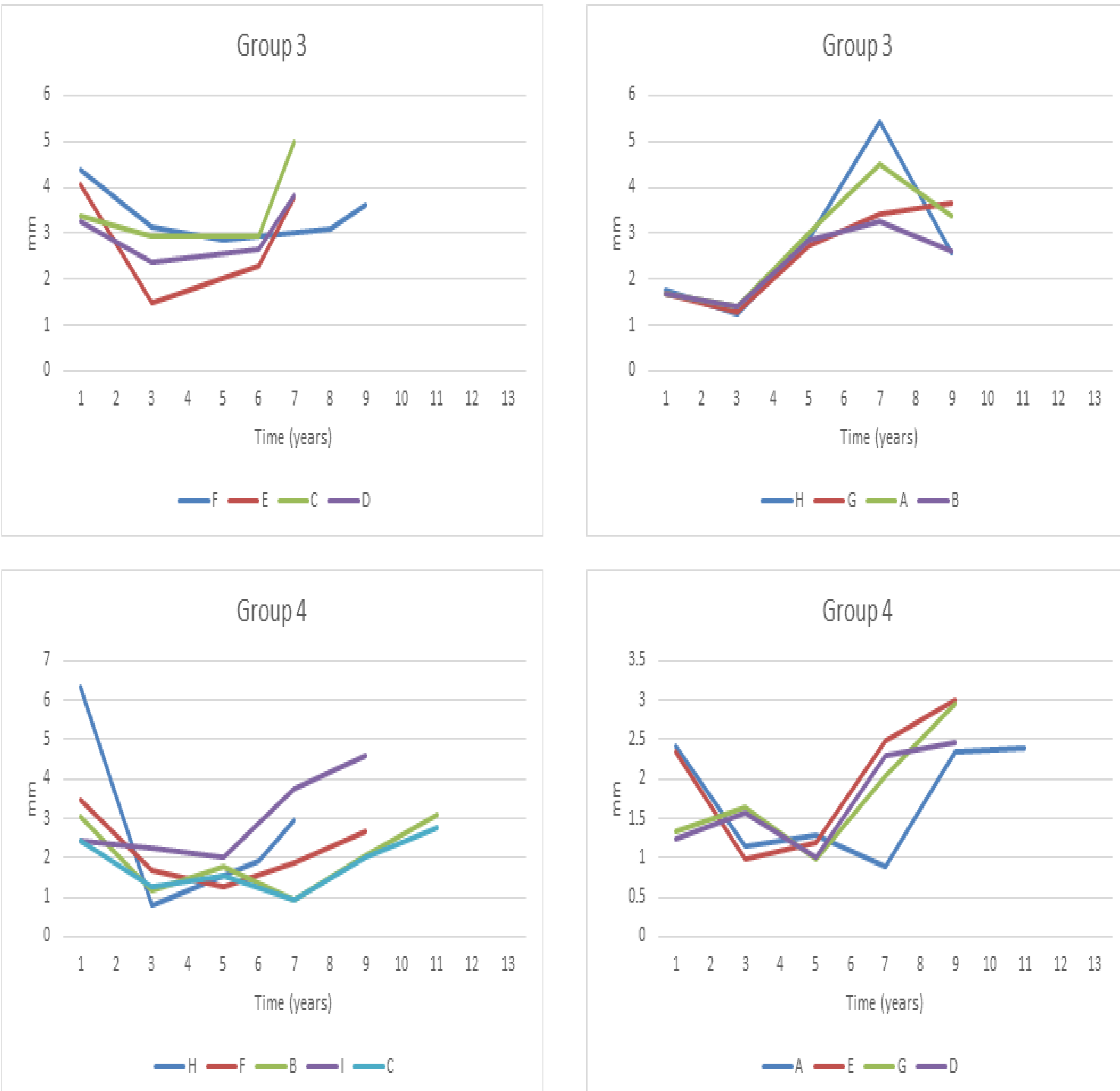

Figure 23. Rut depth for right wheelpath deterioration for Groups 3 and 4

Figure 24. Rut depth for left wheelpath deterioration for Groups 1 and 2

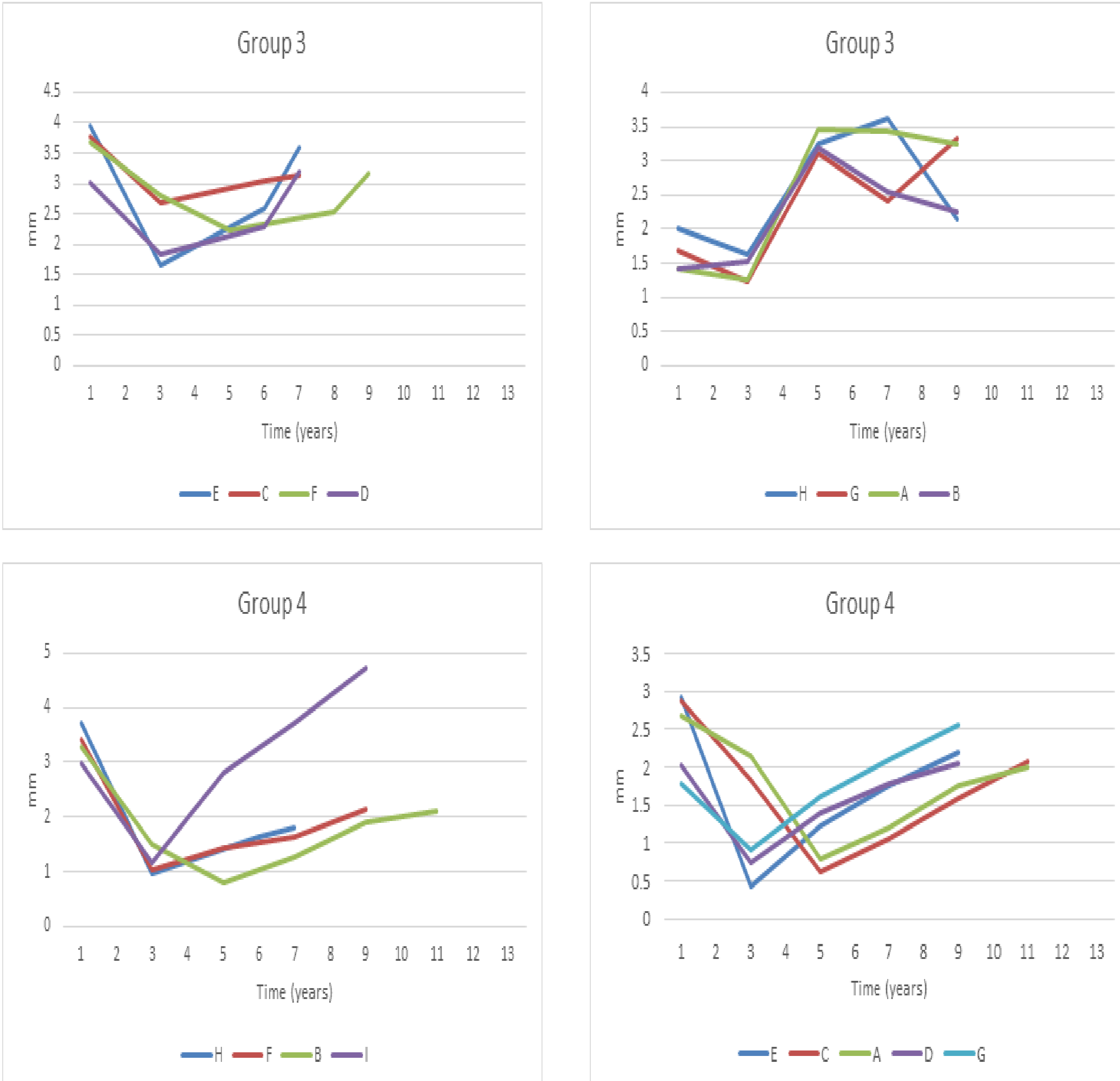

Figure 25. Rut depth for left wheelpath deterioration for Groups 3 and 4

International Roughness Index

Similar to rutting, performance of road roughness was monitored for both the left and right wheelpaths. Figures 26 through 28 show the rate of deterioration for IRI on the left and right wheelpaths. It was observed that IRI was the most consistent performance measurement since the majority of segments had clear short-term and long-term performance patterns.

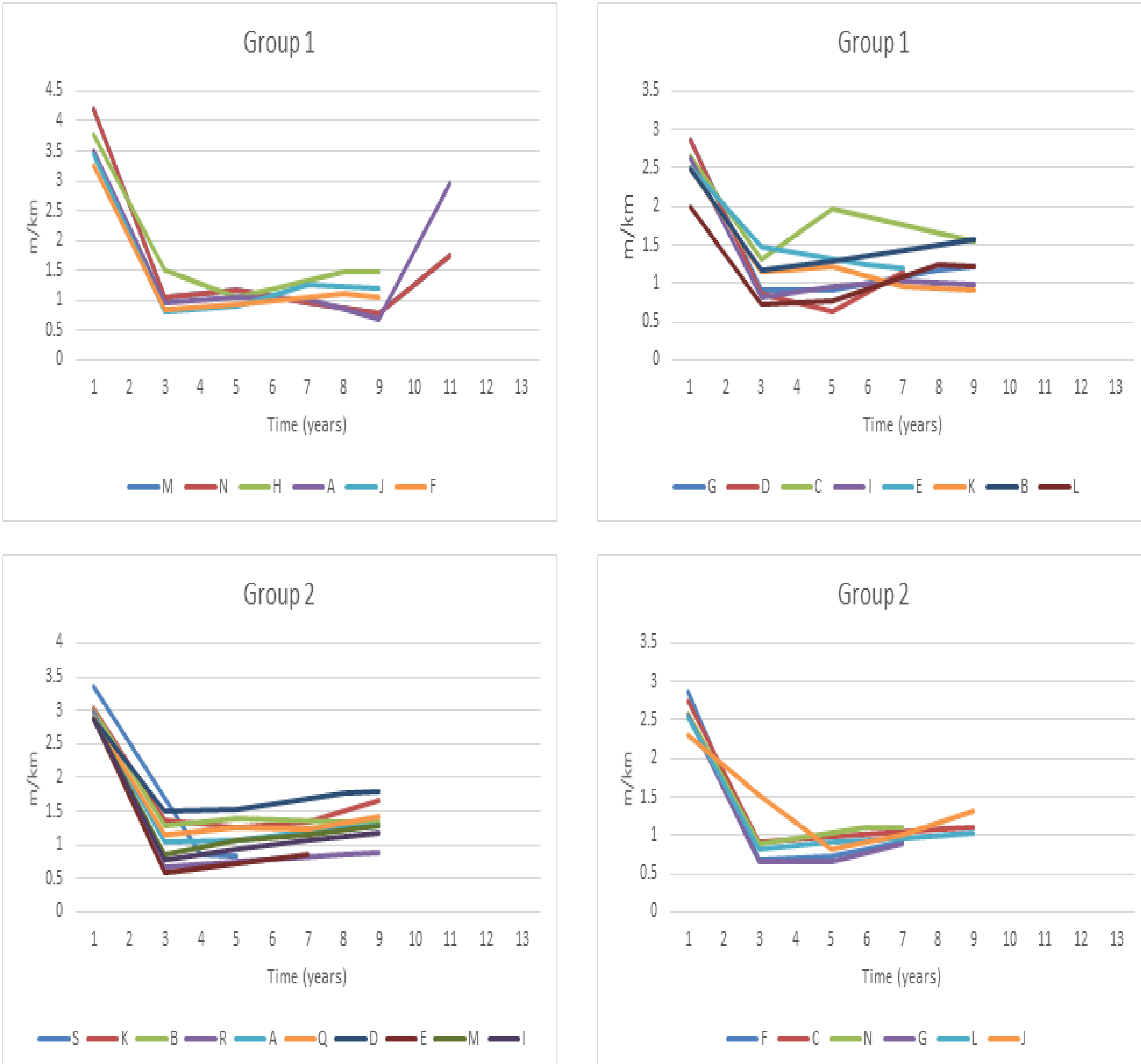

Figure 26. IRI for left wheelpath deterioration for Groups 1 and 2

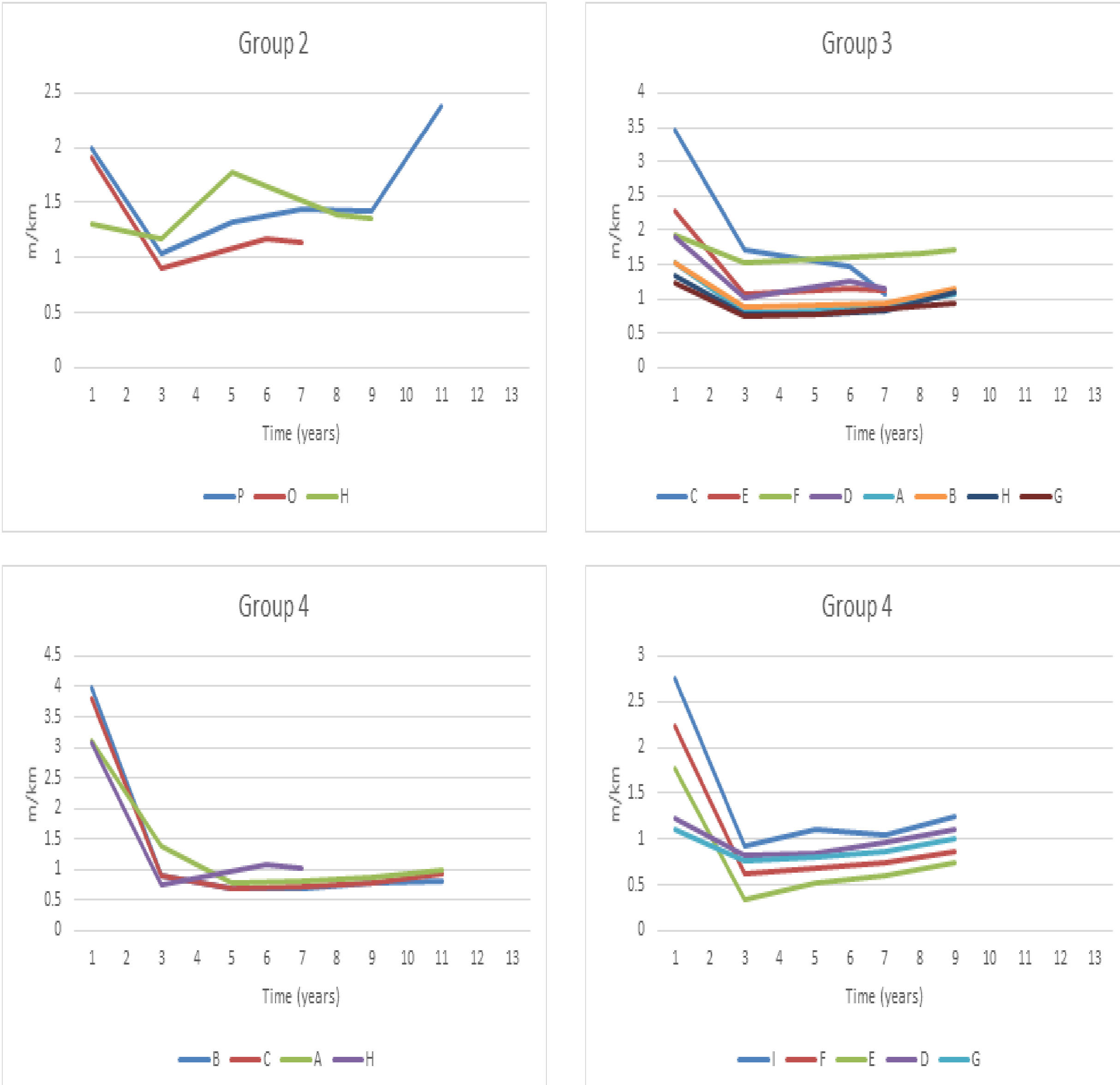

Figure 27. IRI for left wheelpath deterioration for Groups 2, 3, and 4

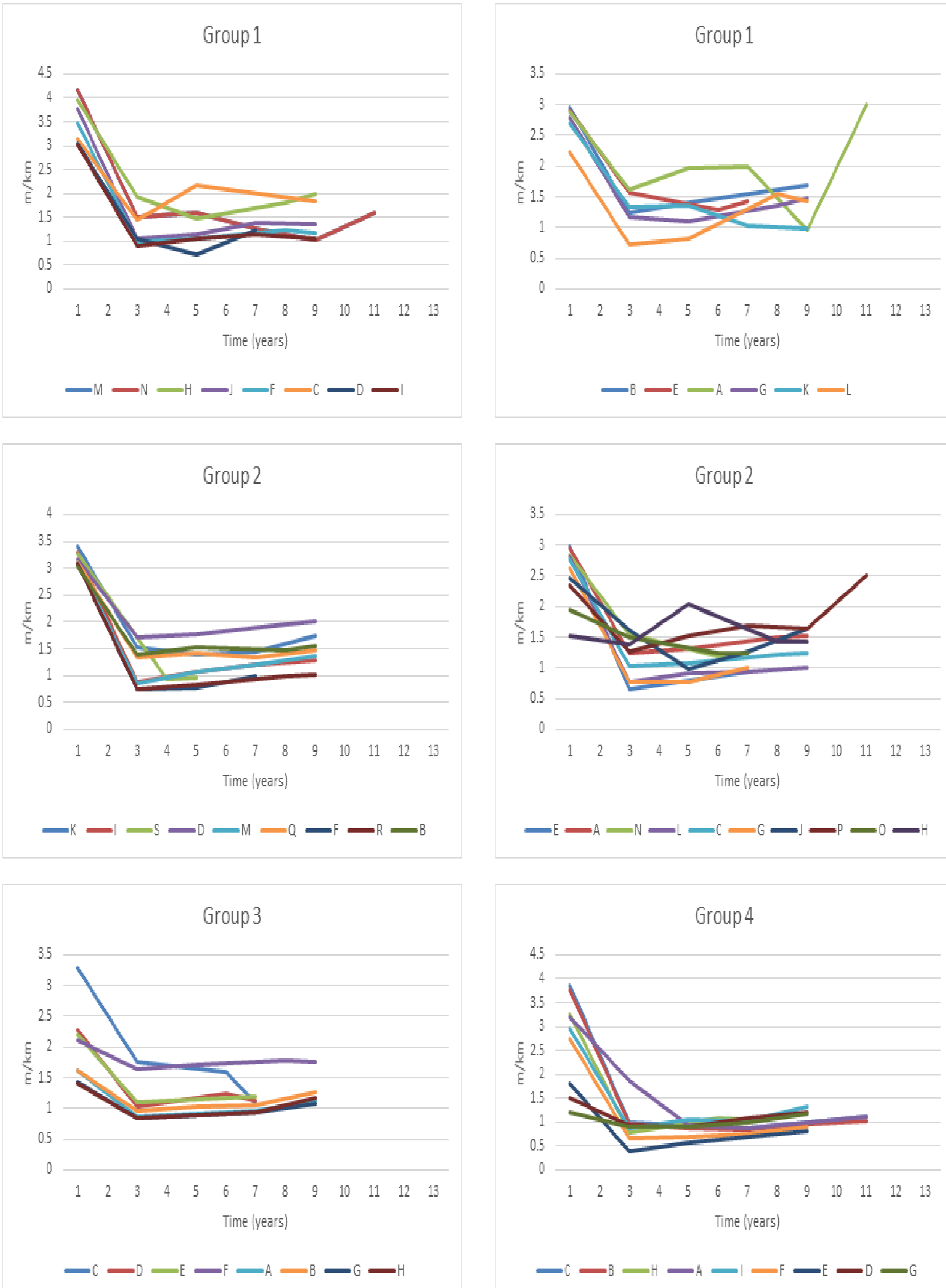

Figure 28. IRI for right wheelpath deterioration for Groups 1, 2 ,3, and 4

Composite Pavements with JPCP

Composite pavements with JPCP received three different rehabilitation treatments. In the following subsections, key observations about the performance of each rehabilitation treatment is discussed.

HMA Resurfacing

For HMA resurfacing on composite pavements, the average pavement thicknesses after overlay were 383, 401, and 273 mm while the average overlay thicknesses were 76, 98.5, and 204 mm for Groups 1, 2, and 3, respectively. The number of segments in each group are as follows:

- Group 1 had 9 segments
- Group 2 had 14 segments
- Group 3 had 2 segments
- Group 4 had 1 segment

The individual distress deterioration patterns for HMA resurfacing on composite pavements are included in Appendix A. It was found that rutting and IRI had a clear performance jump after treatment application and had a regular long-term deterioration pattern. As for alligator cracking, segments have shown good performance over the analysis period, since they exhibited a very low extent level of alligator cracking.

In terms of transverse cracking, the majority of segments exhibited significant performance jumps after treatment application. In terms of low severity transverse cracking, segments had a regular long-term deterioration pattern. However, many segments had different rates of crack propagation. For instance, Segments A and B in Group 1 had a very steep rate of increase from year five to year seven. After year seven, the rate of increase has decreased to be significantly different when compared to the previous rate of deterioration. As for moderate and high severity transverse cracking, the majority of segments did not exhibit any regular deterioration patterns.

The deterioration pattern for low severity longitudinal cracking was similar to the deterioration pattern of low severity transverse cracking. Most of the segments showed significant performance jumps after treatment application. At the same time, many segments had an irregular rate of deterioration over time. As for moderate and high severity longitudinal cracking, few segments showed abrupt performance jumps in the long term while the majority of the segments had a regular deterioration pattern.

HMA Resurfacing with Milling

Similarly, HMA resurfacing with milling on composite pavements segments were categorized into three groups:

- Group 1 had 12 segments
- Group 2 had 7 segments
- Group 3 has 5 segments

HMA resurfacing with milling was not applied on segments with high traffic loadings (i.e., Group 4).

The average pavement thicknesses after overlay were 337, 385, and 376 mm while the average overlay thicknesses were 116, 90, and 133 mm for Groups 1, 2, and 3, respectively. The average milling thicknesses were 60, 46, and 62 mm for Groups 1, 2, and 3, respectively.

The individual distress deterioration patterns for HMA resurfacing with milling on composite pavements are included in Appendix B. Similar to other treatments, rutting and IRI had regular deterioration patterns over time. As for alligator cracking, the majority of segments exhibited good performance except for Segment D in Group 1 and Segment C in Group 3. The two segments did not have high extent alligator cracking before treatment application and thus their poor performance was not related to their pretreatment condition.

As for longitudinal and transverse cracking, similar patterns were observed when compared to other treatments. However, segments exhibited good performance in terms of high severity longitudinal and transverse cracking.

HMA Resurfacing with CIPR

HMA resurfacing with CIPR on composite pavements were applied to 11 segments. The minimum ESAL for those segments was 16,872 while the maximum ESAL was 87,479. As such, these segments were grouped together for individual distress analysis. The average pavement thickness after overlay was 386 mm while the average overlay thickness was 84 mm.

The individual distress deterioration patterns for HMA resurfacing with CIPR are included in Appendix C. It was observed that the deterioration of rutting over time for many segments did not follow any regular pattern. However, deterioration of ride quality for the majority of segments did follow a regular pattern. As for alligator cracking, segments showed good performance over the long term. In terms of low and moderate severity longitudinal and transverse cracking, segments showed an irregular pattern of deterioration over time. However, a good performance was observed in terms of high severity longitudinal and transverse cracking.

Composite Pavements with JRCP

Twelve composite pavements with JRCP were analyzed in this study. These pavement segments mainly received HMA resurfacing with milling. The performance of this treatment was analyzed in the following subsection.

HMA Resurfacing with Milling

Twelve pavement segments received HMA resurfacing with milling. The minimum ESAL for those segments was 612,279 while the maximum ESAL was 951,141. As such, these segments were grouped together for individual distress analysis. The average pavement thickness after overlay was 366 mm while the average overlay thickness was 106 mm. The average milling thickness was 97 mm.

The individual distress deterioration patterns for HMA resurfacing with milling are included in Appendix D. In terms of rutting, IRI, and alligator cracking, segments showed similar performance to other treatments. In terms of low and moderate severity transverse cracking, six segments exhibited a steady increase in long-term patterning while the other segments exhibited an irregular deterioration pattern. It was also observed that segments performed very well in terms of high severity transverse and longitudinal cracking.

In terms of low severity longitudinal cracking, it was observed that the majority of the segments had a steady rate of deterioration over time.

AC Pavements

AC pavements segments mainly received HMA resurfacing with CIPR. As such, the performance of HMA resurfacing with CIPR was analyzed in the following subsection.

HMA Resurfacing with CIPR

Thirteen segments receiving HMA resurfacing with CIPR on flexible pavements were analyzed in the study. The minimum ESAL for those segments was 8,942 while the maximum ESAL was 46,526. As such, these segments were grouped together for individual distress analysis. The average pavement thickness after overlay was 296 mm while the average overlay thickness was 91 mm.

The individual distress deterioration patterns for HMA resurfacing with CIPR on AC pavements are included in Appendix E. Similar to other treatments, rutting and IRI had regular patterns of deterioration.

In terms of moderate alligator cracking, six segments did not perform well on the long term when compared to the pretreatment condition. On the other hand, all segments performed very well in terms of high severity alligator cracking.

As for low and moderate transverse and longitudinal cracking, the majority of the segments did not have any regular deterioration patterns. However, segments exhibited good performance in terms of high severity transverse and longitudinal cracking.

Summary of Performance Evaluation

Based on the individual distress evaluation, it was found that rutting and IRI are the most consistent performance indicators while other distresses did not exhibit regular long-term performance patterns.

The following factors may be the main reasons behind the irregular patterns of the other distresses:

- Performing undocumented in-house maintenance
- Recording sealed cracks as low severity cracks
- Crack transformation from one type to another
- Errors in distress measurement and recording

It was found that the Iowa DOT performs in-house maintenance activities such as crack sealing/filling and patching to mitigate the rate of pavement deterioration, which affects the deterioration patterns of individual distresses. However, these common in-house maintenance activities are currently not documented. Additionally, it is common DOT practice to record sealed cracks as low severity cracks and hence the pattern of crack deterioration is irregular. Recording sealed cracks as low severity cracks may also be the reason behind the increasing rate of low severity crack propagation. Because of the irregular deterioration patterns for several distresses, it was decided to use observational historical data only. Additionally, any performance predictions were very questionable and unreliable.

In summary, rutting and IRI have a clear and logical pattern of deterioration while other cracking distress data have decreased and increased over time because of the aforementioned reasons. Therefore, using cracking condition data to evaluate treatment performance is challenging because of the lack of in-house maintenance data and the existing irregular patterns.

ESTIMATION OF TREATMENT SERVICE LIVES

In the literature, the estimation of pavement treatment service life was conducted using the following methods:

- Pavement condition hit a specific threshold value
- Pavement post-treatment condition was almost equal to the pretreatment condition
- Application of another rehabilitation treatment

The first method relies on setting a specific threshold value that reflects the acceptable level of service from the highway agency management perspective. Therefore, the treatment service life is terminated when the pavement condition hits the set threshold value. The second method relies on comparing the post-treatment condition with the pretreatment condition. Similarly, the treatment service life is terminated when the post-treatment condition is almost equal to the pretreatment condition. Finally, in the third method, the treatment service life of a treatment is terminated when another major maintenance or rehabilitation treatment is applied after the original treatment application.

In the study, the performance evaluation of a treatments was conducted by comparing the post-treatment against the pretreatment condition to determine the service life of the treatment. Additionally, the service life of a treatment was terminated if a performance jump was observed during the service life of the treatment, which indicated the application of another maintenance or rehabilitation treatment.

In order to visualize the performance evaluation concept and terminology, Figure 29 shows the typical pattern of observed performance jumps for rutting and IRI.

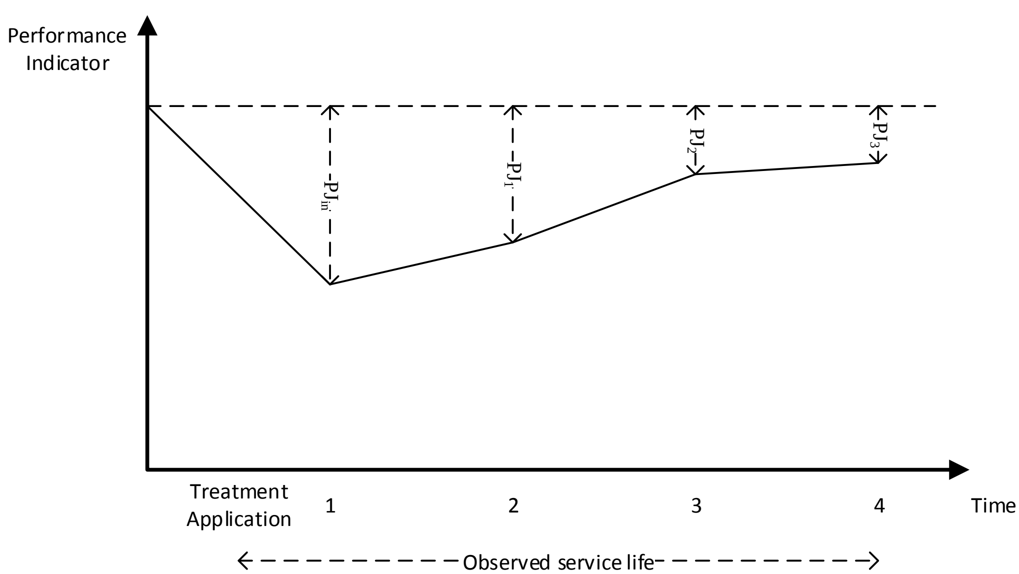

Figure 29. Performance jumps for performance indicators and observed service life

A significant performance jump was observed immediately after treatment application. Afterwards, the performance jump kept decreasing over time as the pavement condition continued to deteriorate. Typically, the treatment service life is terminated at year (t) when the performance jump at year (t) is close to zero. However, the study used observational historical condition data to evaluate the treatment performance. Thus, in many cases the observed performance jump at the last observed year was greater than zero, which indicated the existence of remaining service life for the treatment. As such, it was expected that the actual average service life for the treatments under evaluation would be longer than the ones estimated in this study.

Significance Testing

Two statistical significance tests were conducted to investigate whether the rehabilitated pavement post-treatment condition was significantly higher than the pretreatment condition at the end of the observed service life. The first test was a paired t-test while the other test was a distribution free non-parametric Wilcoxon singed rank test. Tables 5 and 6 show the test results for each treatment type and the average observed service life in terms of ride quality and rutting.

Table 5. Significance testing using IRI data

Pavement Type	Treatment Type	Number of Records	T-test Statistic (p-value)	Wilcoxon Signed Rank Test statistic (p-value)	Min., Avg., and Max. Service Life
PCC	HMA resurfacing	100	(1.15×10^{-34})	(6.2×10^{-18})	(3, 6.6, 9)
Composite with JPCP	HMA resurfacing	49	(2.08×10^{-15})	(1.3×10^{-8})	(5, 7.6, 12)
	HMA resurfacing with milling	48	(4.15×10^{-16})	(4.72×10^{-9})	(5. 6.6, 9)
	HMA resurfacing with CIPR	20	(3.29×10^{-11})	(8.86×10^{-5})	(3, 4.8, 7)
Composite with JRCP	HMA resurfacing with milling	24	(4.75×10^{-5})	(0.0014)	(5, 5.3, 7)
AC	HMA resurfacing with CIPR	26	(1.07×10^{-12})	(3.78×10^{-6})	(7, 8.9, 13)

Table 6. Significance testing using rutting data

Pavement Type	Treatment Type	Number of Records	T-test Statistic (p-value)	Wilcoxon Signed Rank Test Statistic (p-value)	Min., Avg., and Max. Service Life
PCC	HMA resurfacing	96	(3.89×10^{-13})	(1.77×10^{-17})	(1, 4.9, 9)
Composite with JPCP	HMA resurfacing	49	(7.66×10^{-10})	(4.34×10^{-8})	(3, 6.7, 12)
	HMA resurfacing with milling	48	(3.20×10^{-10})	(1.63×10^{-9})	(3, 6.1, 9)
	HMA resurfacing with CIPR	19	(1.36×10^{-5})	(1.32×10^{-4})	(1, 3.4, 7)
Composite with JRCP	HMA resurfacing with milling	24	(9.36×10^{-9})	(2.59×10^{-5})	(5, 5.3, 7)
AC	HMA resurfacing with CIPR	26	(9.27×10^{-8})	(8.29×10^{-6})	(1, 6.5, 9)

According to the significance testing results, it was found that the post-treatment pavement condition, in terms of IRI and rutting and the last survey data available, was significantly better than the pretreatment pavement condition.

TREATMENT PERFORMANCE COMPARISON

It is necessary to compare the performance of different treatments when traffic loadings are similar. Composite pavement projects received the three different treatments that were evaluated in the study. As such, the performance of the different treatments were evaluated in terms of ride quality to investigate whether a specific pavement treatment was superior to others under similar conditions. The analysis of treatment performance was conducted using a one-way ANOVA test and t-test.

The performance of the three treatments was analyzed for Group 1, which represented the lowest traffic loading. Additionally, a comparison between HMA resurfacing with milling and HMA resurfacing was conducted for Group 2, which had higher traffic loadings.

The first step when the performance of different treatments were compared for segments in Group 1 was to assure the similarity between the segments. The null hypotheses included the following:

- The means of ESAls were not significantly different.
- The means of pretreatment IRI were not significantly different.

The ANOVA test was conducted and it was found that the variances between ESALs and pretreatment IRI for the three groups were not significant. As such, the ANOVA test was conducted to test if there is a significant difference between the performance of the three treatments in terms of ride quality.

IRI data measured after seven years was used to unify the service life between treatments. It was also found that the majority of segments had condition survey data after seven years or more. However, some segments didn’t have IRI measurements after exactly seven years but had IRI measurement before and after year seven. In those cases, a linear relationship was assumed to estimate the IRI measurement at year seven. Figure 30 shows the overall test procedure used to compare the performance of the three different treatments.

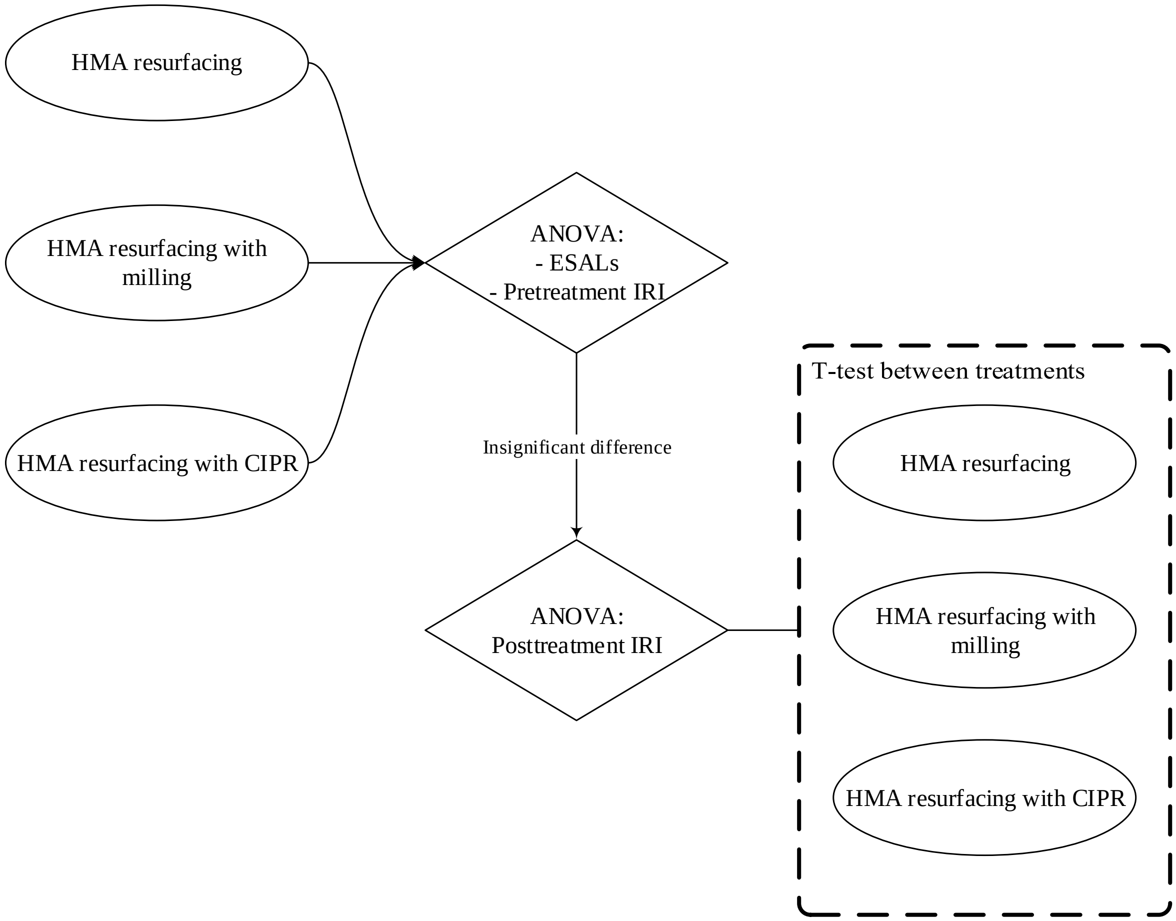

Figure 30. Overall test procedure used for performance comparison of treatments

Based on the ANOVA test results, a significant difference was found between the post-treatment IRI population means. It was concluded that there were significant differences between the performances of the three treatments. A t-test was conducted to determine what treatment had the better performance.

It was found that HMA resurfacing with CIPR performed better when compared to HMA resurfacing and HMA resurfacing with milling. However, the HMA resurfacing and HMA resurfacing with milling had no significant difference in performance in the two groups. However, it was not feasible to determine what treatment was the best performer on the long term (i.e., 15 to 20 years) because of data collection limitations.

RECOMMENDATIONS

During the past two decades, many SHAs started to collect pavement management data including pavement distresses, materials, pavement roughness, friction, traffic, and so forth. Agencies are benefiting from this collected data by improving their decision-making processes through redefinition of their data management practices. However, a full return on their investment has not been fully realized because of some existing issues hindering data usage and analysis. This chapter presents necessary recommendations that can improve the future use of Iowa pavement management data.

Maintenance and Rehabilitation Data

First, the location of maintenance and rehabilitation projects need to be recorded accurately. Many projects found in this study had inaccurate latitude and longitude data, as the location data provided did not coincide with the known project route. It is recommended that multiple points with latitudes and longitudes within narrow proximity of the specified project location should be collected. This would allow the agency to quickly detect and discard inaccurate location data. In addition, the location data should represent the midpoint of the project. If this is not the case, it is recommended that location data should be described using textual information using descriptors like starting point, end point, midpoint, or unspecified.

Maintenance and rehabilitation data should also include key pieces of information that are needed for pavement performance analysis. For instance, HMA resurfacing with CIPR should include the percentage of recycled material. Additionally, other overlay projects should include inputs that affect the performance of pavement such as binder content, binder type, and air void percentages. In addition, basic project information such as overlay and milling thickness should be recorded appropriately.

Pavement Distress Data

The pavement distress propagation for many sections in this study had irregular patterns. These irregular patterns were a result of unrecorded in-house maintenance projects and distress recording practices. Since the Iowa DOT records sealed cracks as low severity cracks, it is recommended that agencies instead record sealed cracks separately or record the percentage of sealed cracks. Also, the purpose of patching, when applied over time, should be recorded in a separate field, especially when addressing high severity distress. Future pavement performance data can be better utilized at the distress-level scale if this information is recorded.

Additionally, the method of distress data aggregation should be improved to consider different factors such as severely localized sections, segment length inconsistencies, and so forth.

SUMMARY AND CONCLUSIONS

This study evaluated the performance of three major rehabilitation treatments by developing a methodological framework to spatially integrate the Iowa DOT's pavement management data and rehabilitation project data together.

The study framework aimed at integrating the locations of maintenance and rehabilitation projects with the raw pavement condition data. Additionally, the framework used GIS tools and features to spatially extract the pavement condition data for further analysis.

First, the pavement deterioration was analyzed at the distress-level scale. As such, deterioration curves were presented for each segment and for each distress. It was found that IRI and rutting are the most consistent performance indicators. As such, IRI and rutting were used to estimate the service life for each treatment. The study also provided insights into how individual distresses propagate over time and how these trends could affect the treatment evaluation process.

Data management practices need to be improved in order to clarify ambiguities associated with the data collected. Additionally, utilization of collected data can be significantly improved by recording missing data such as in-house maintenance projects.

Based on the analysis of the data, the following conclusions were made:

- Almost all distress propagation over time had irregular patterns and abrupt changes except for IRI. For IRI, pavement deterioration was very consistent when compared to other distresses.
- The use of overall condition indexes such as the PCI or PCR may yield misleading results because of the irregular deterioration pattern of some segments.
- Treatments did not perform well in retarding rutting deterioration when compared to ride quality deterioration.
- For rutting, the average service life of pavement was generally lower than the average service life in terms of ride quality.
- In terms of ride quality, HMA resurfacing with CIPR outperformed HMA resurfacing and HMA resurfacing with milling when traffic loadings were low.

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APPENDIX A. DISTRESS DETERIORATION PATTERNS FOR HMA RESURFACING ON COMPOSITE PAVEMENTS

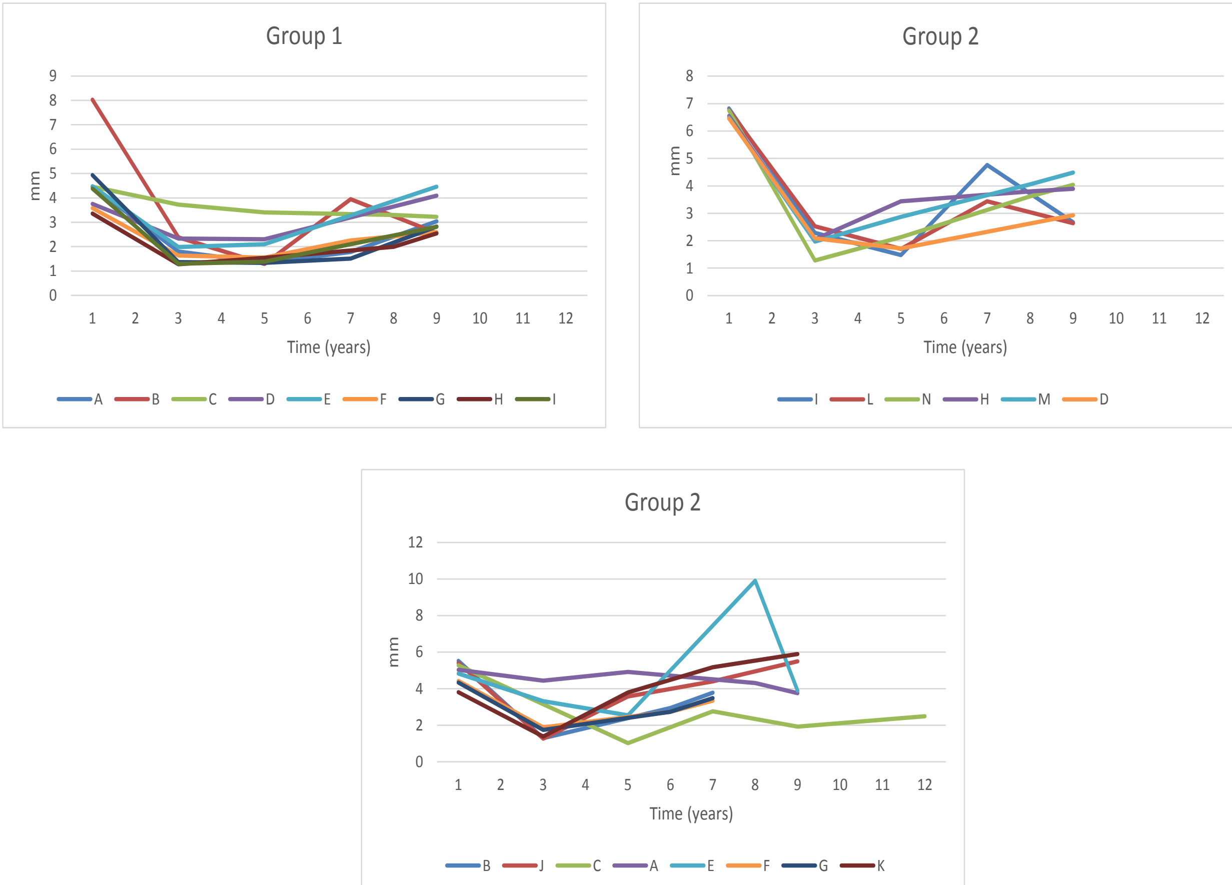


Figure A.1. Rutting on the left wheelpath for Groups 1 and 2

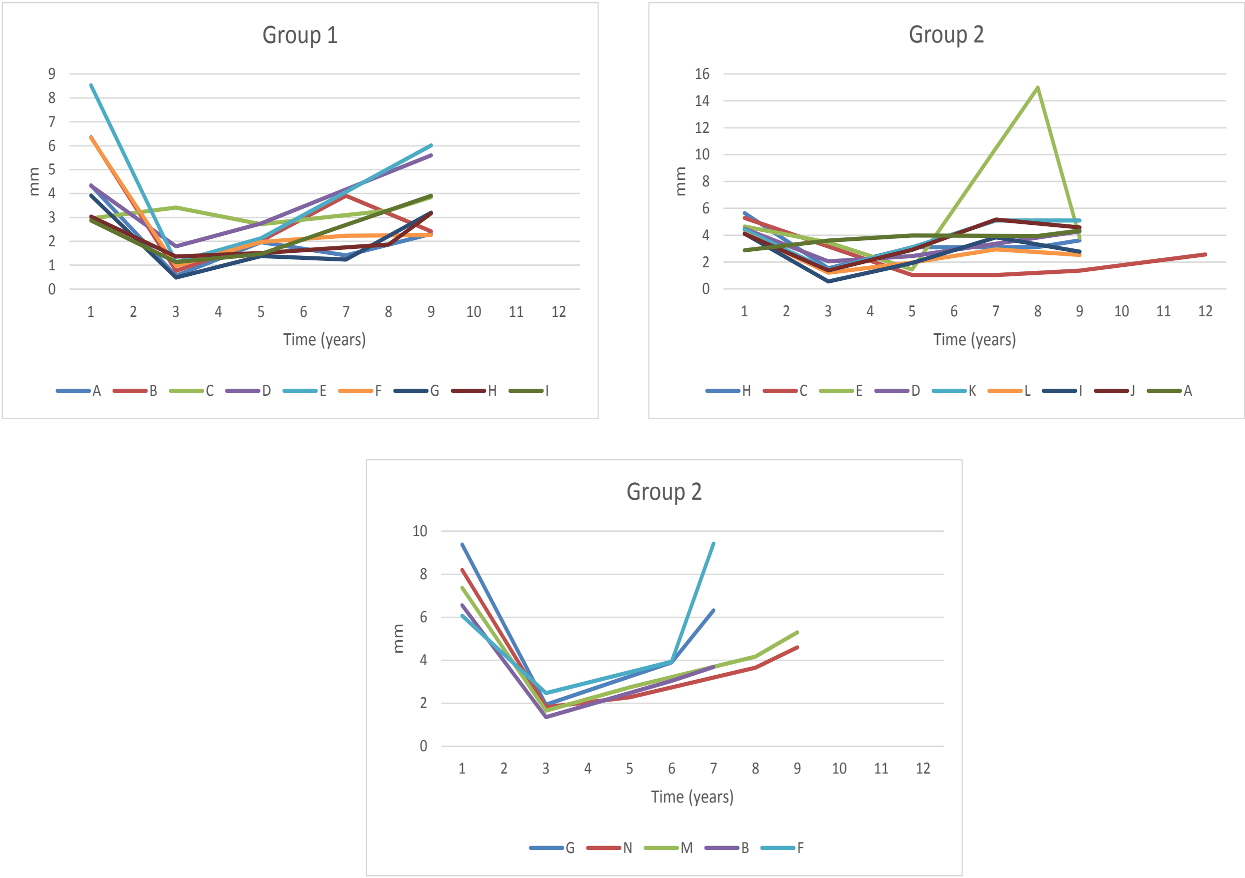


Figure A.2. Rutting on the right wheelpath for Groups 1 and 2

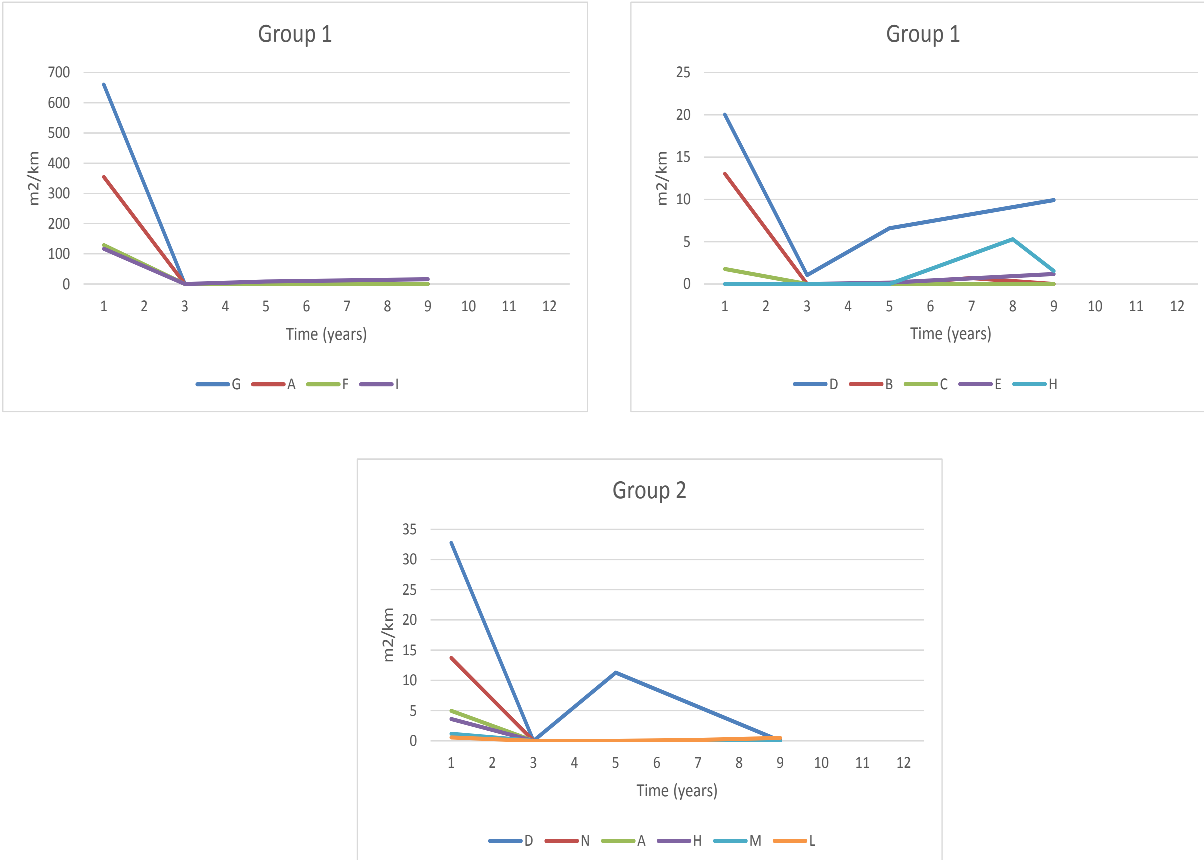


Figure A.3. Moderate severity alligator cracking for Groups 1 and 2

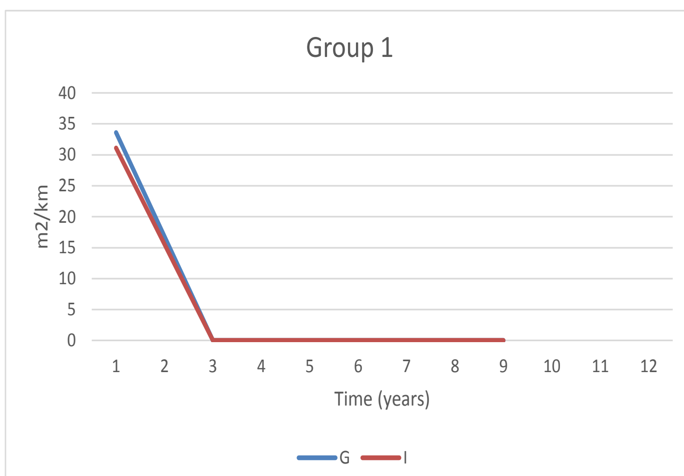


Figure A.4. High severity alligator cracking for Group 1

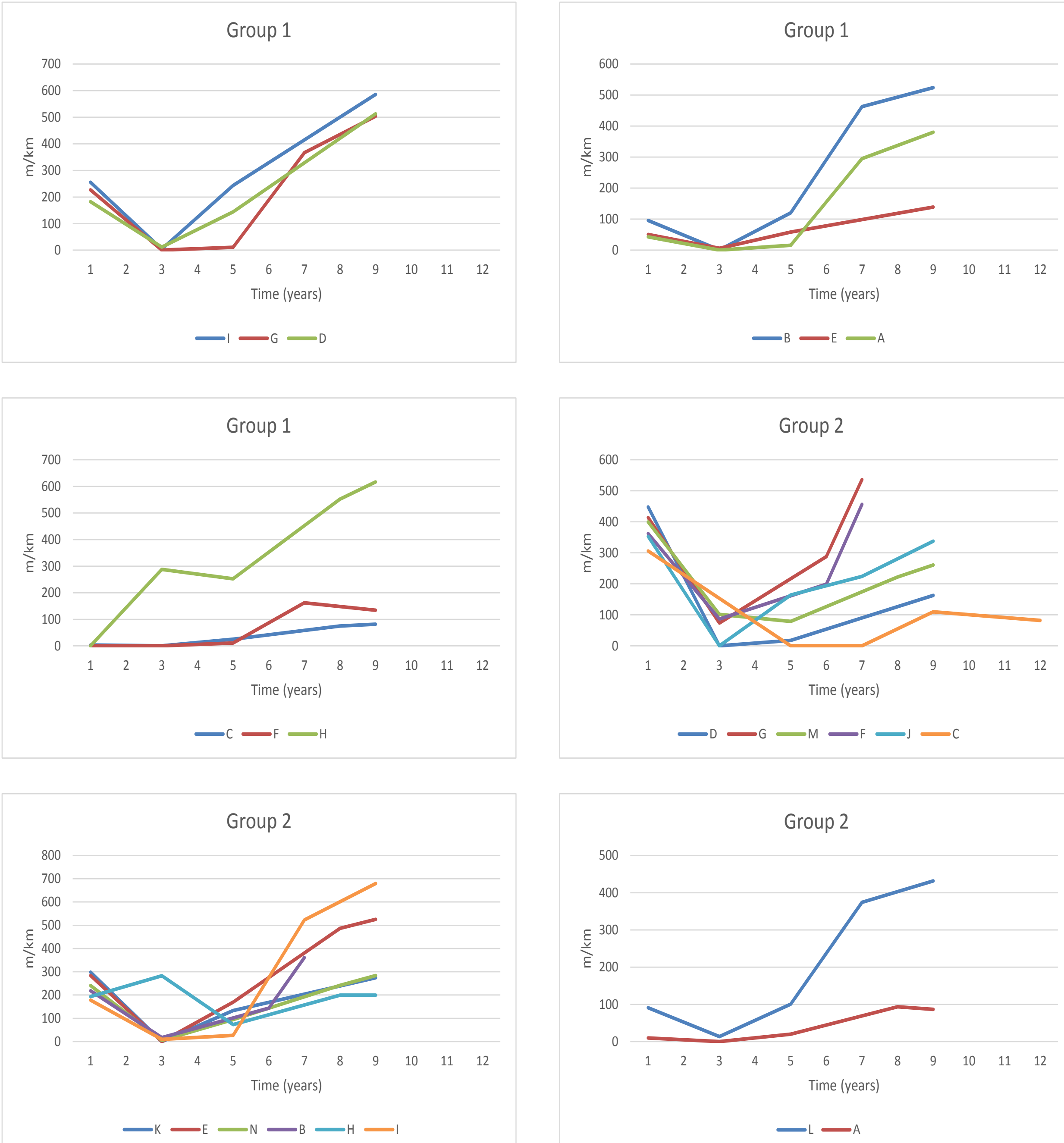


Figure A.5. Low severity transverse cracking for Groups 1 and 2

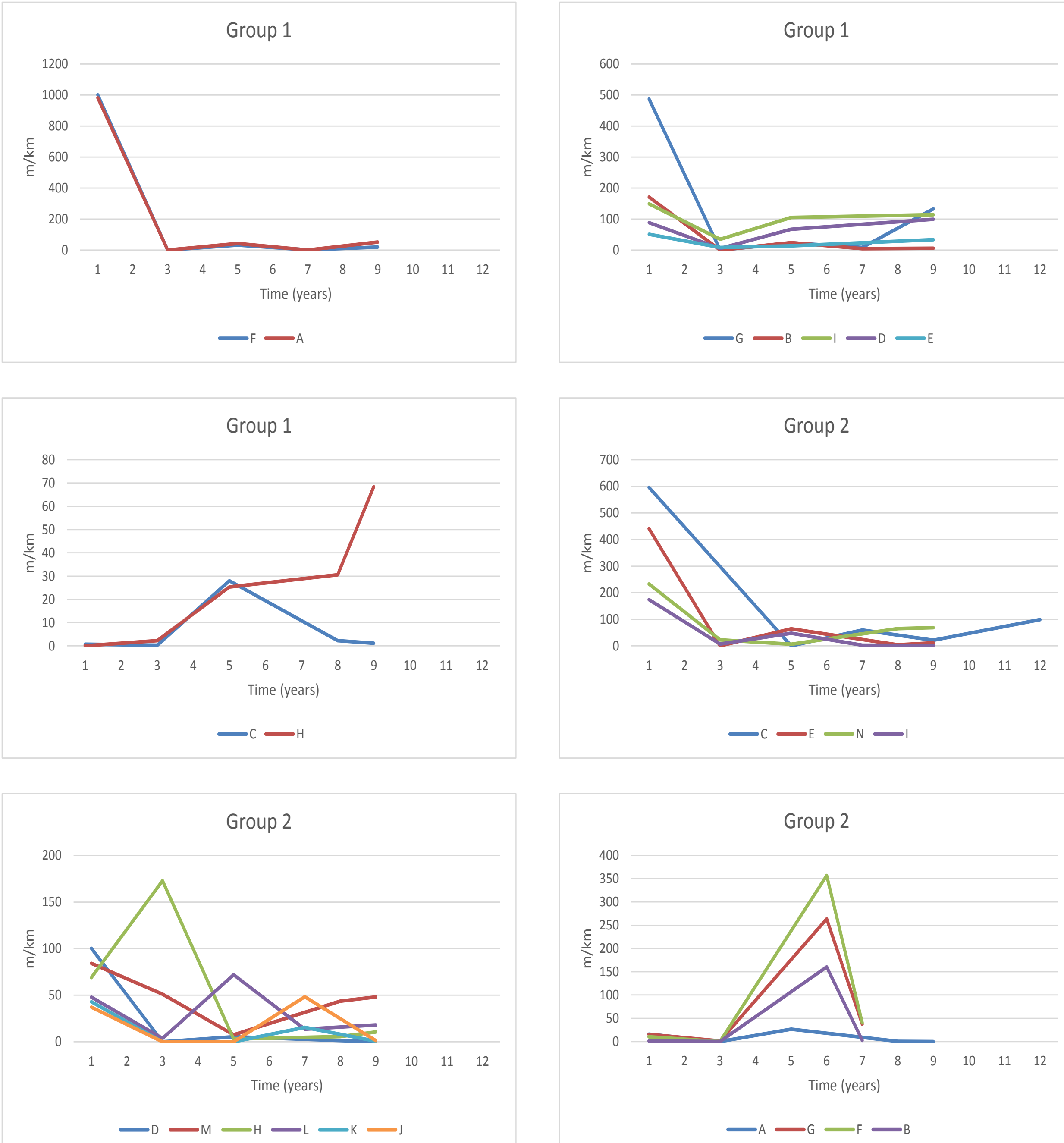


Figure A.6. Moderate severity transverse cracking for Groups 1 and 2

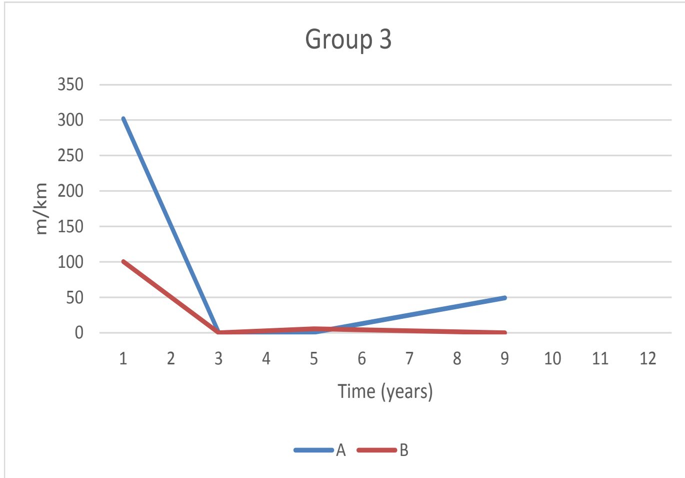


Figure A.7. Moderate severity transverse cracking for Group 3

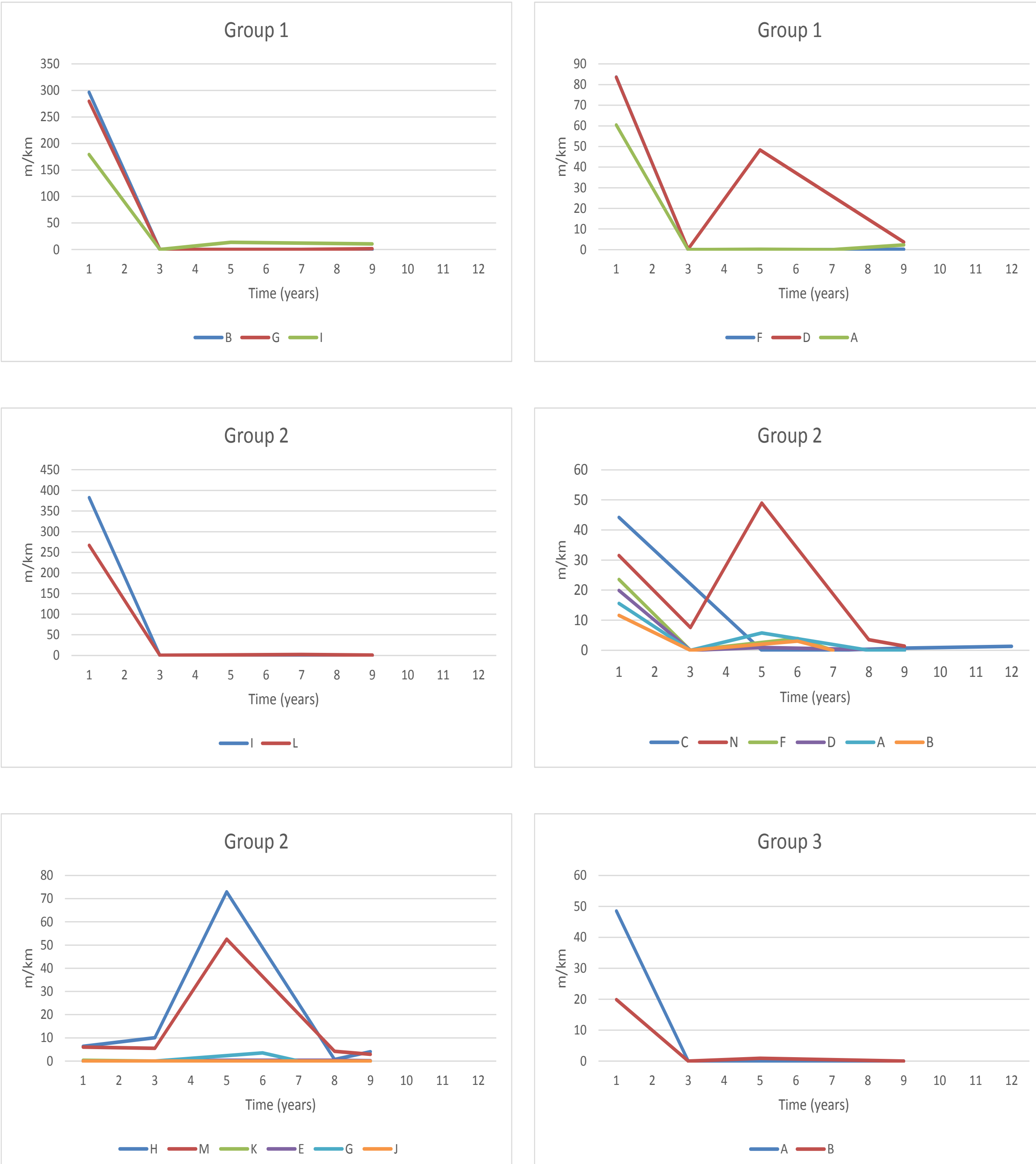


Figure A.7. High severity transverse cracking for Groups 1, 2, and 3

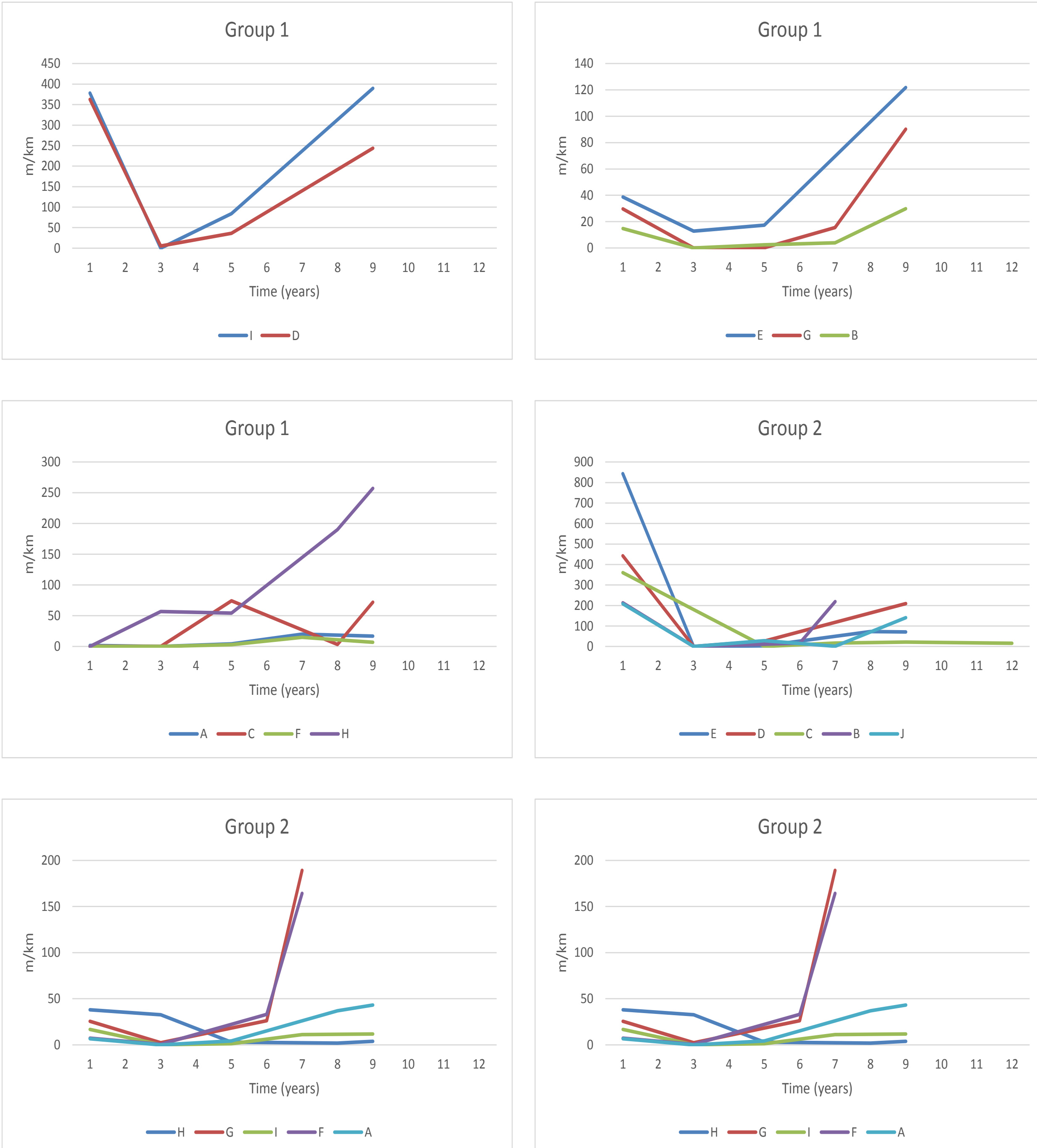


Figure A.8. Low severity longitudinal cracking for Groups 1 and 2

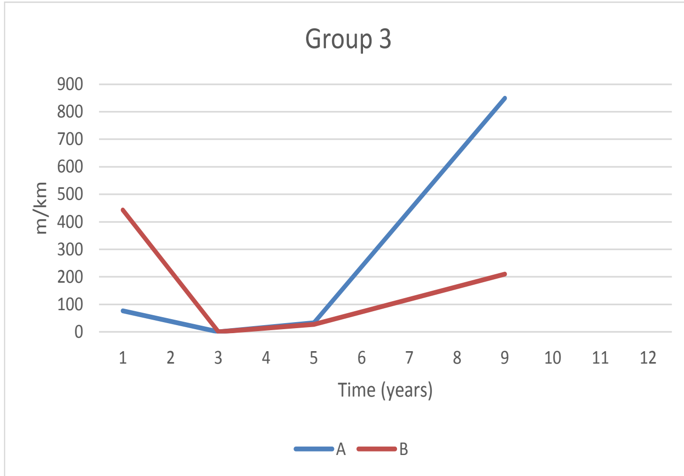


Figure A.9. Low severity longitudinal cracking for Group 3

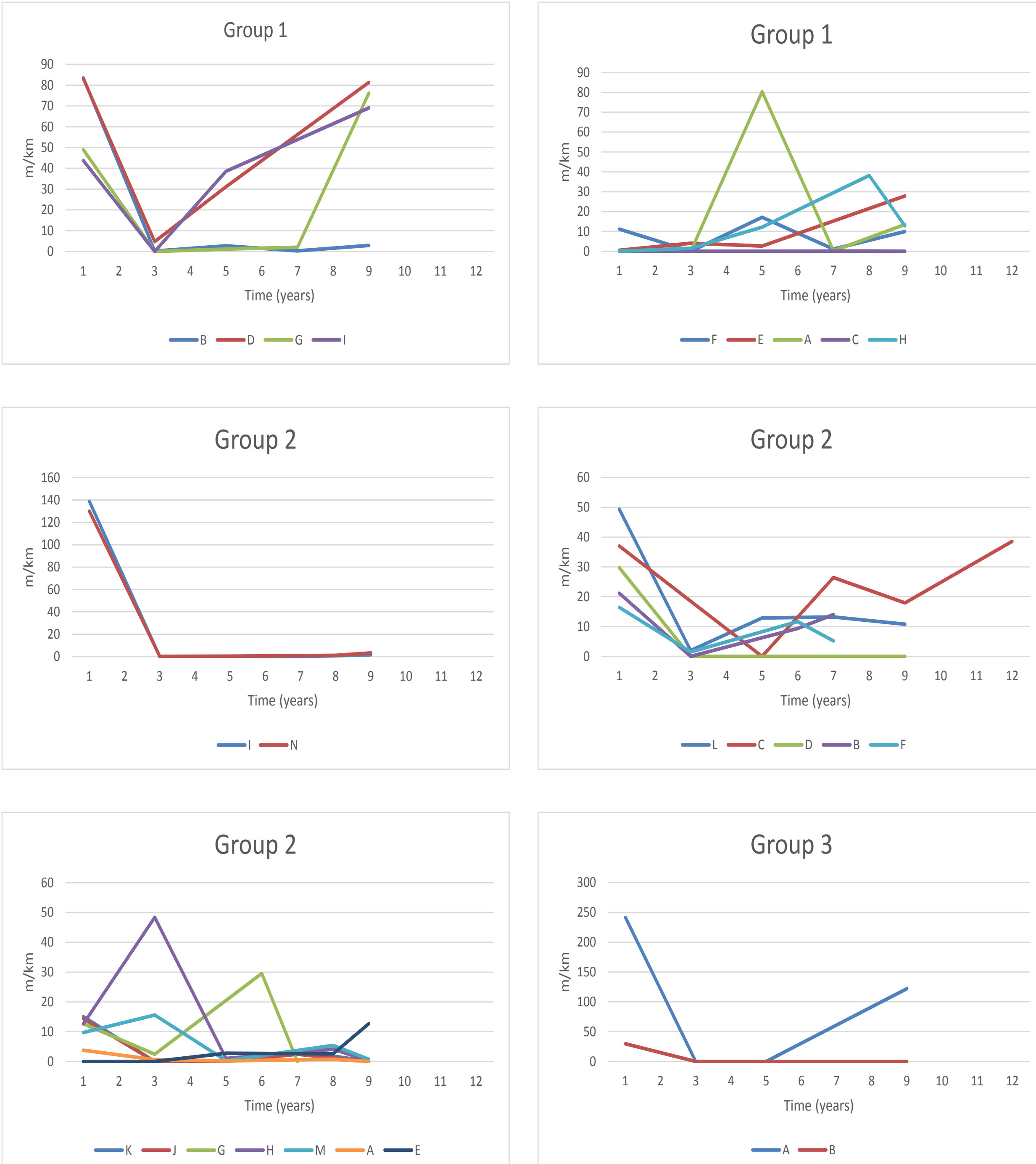


Figure A.10. Moderate severity longitudinal cracking for Groups 1, 2, and 3

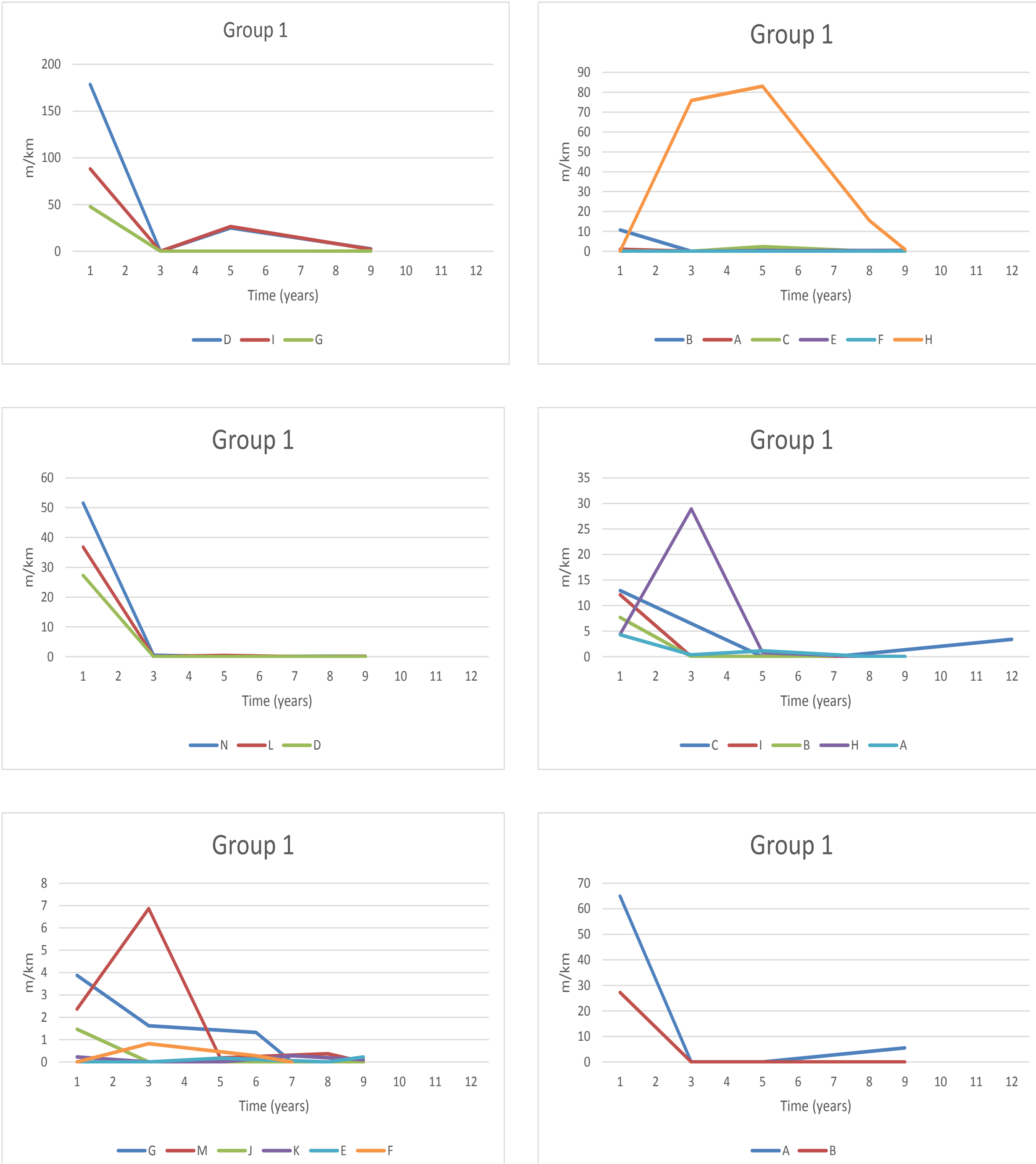


Figure A.11. High severity longitudinal cracking for Group 1

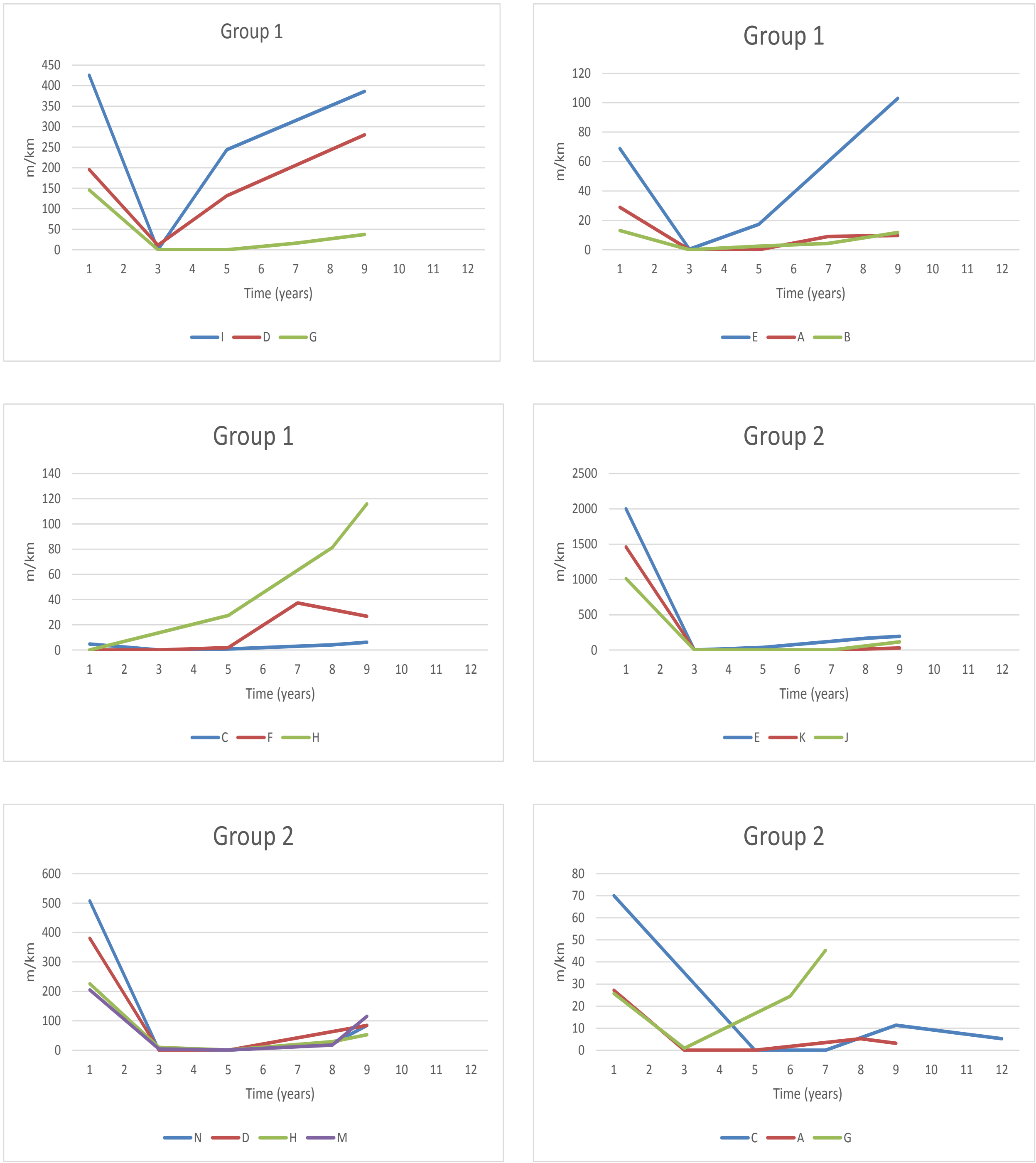


Figure A.12. Low severity longitudinal cracking on wheelpath for Groups 1 and 2

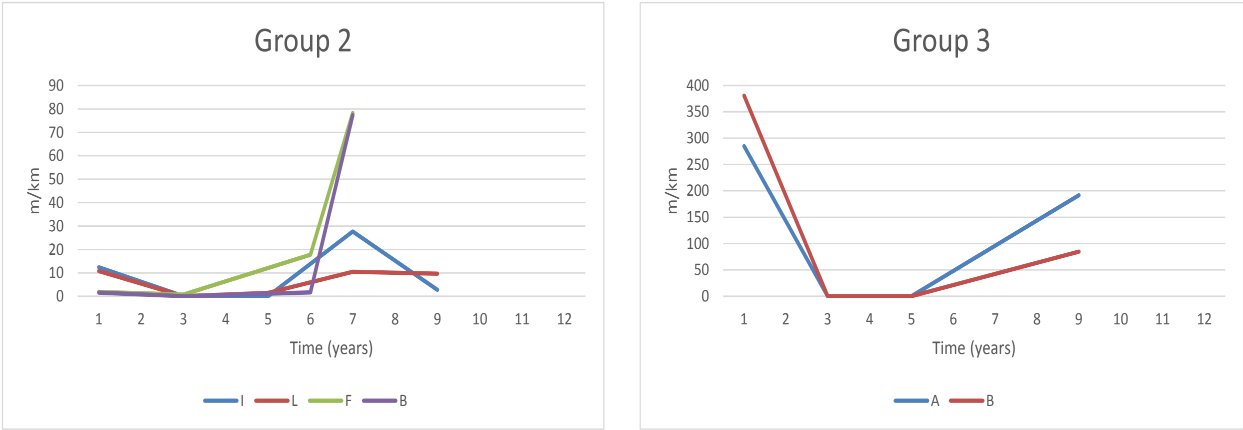


Figure A.13. Low severity longitudinal cracking on wheelpath for Groups 2 and 3

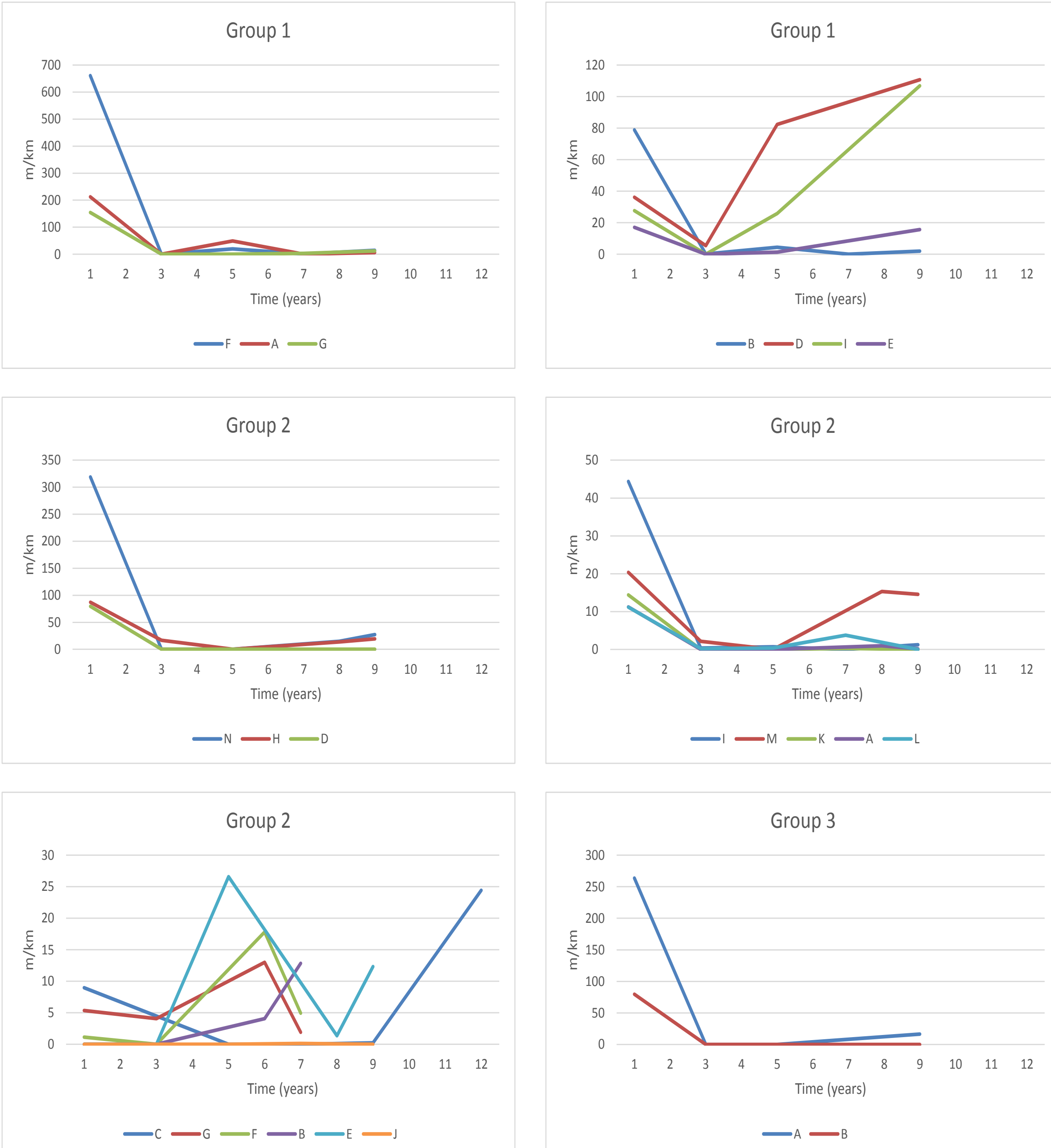


Figure A.14. Moderate severity longitudinal cracking on wheelpath for Groups 1, 2, and 3

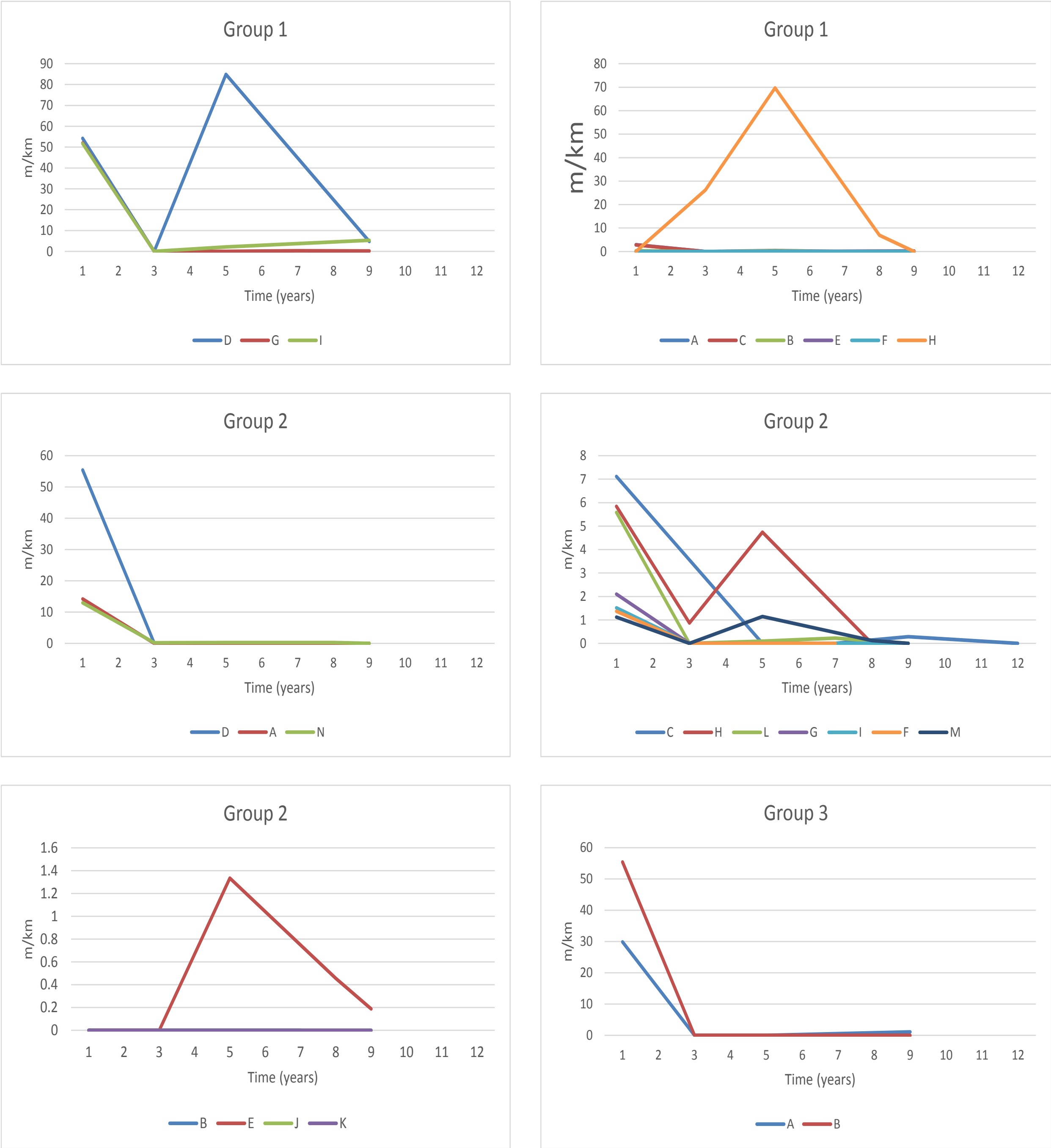


Figure A.15. High severity longitudinal cracking on wheelpath for Groups 1, 2, and 3

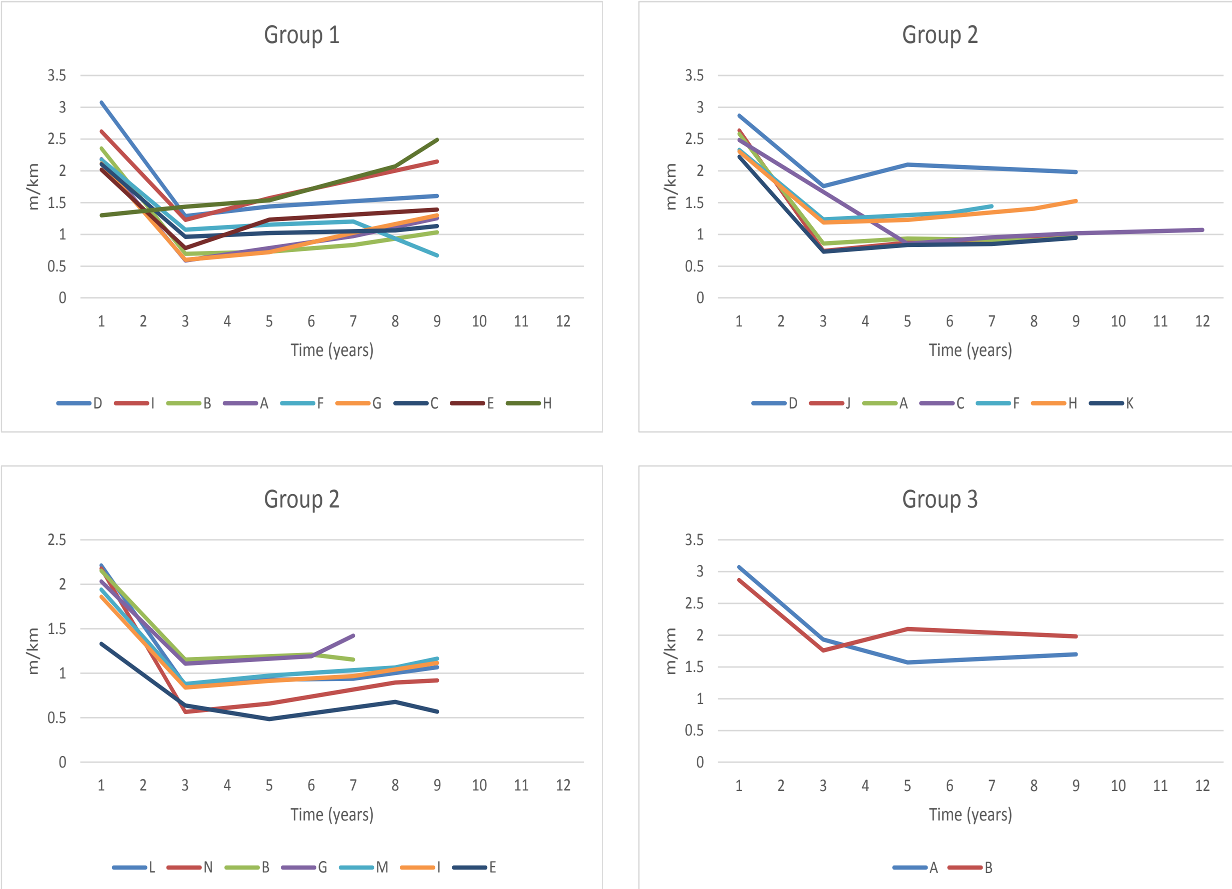


Figure A.16. IRI on the left wheelpath for Groups 1, 2, and 3

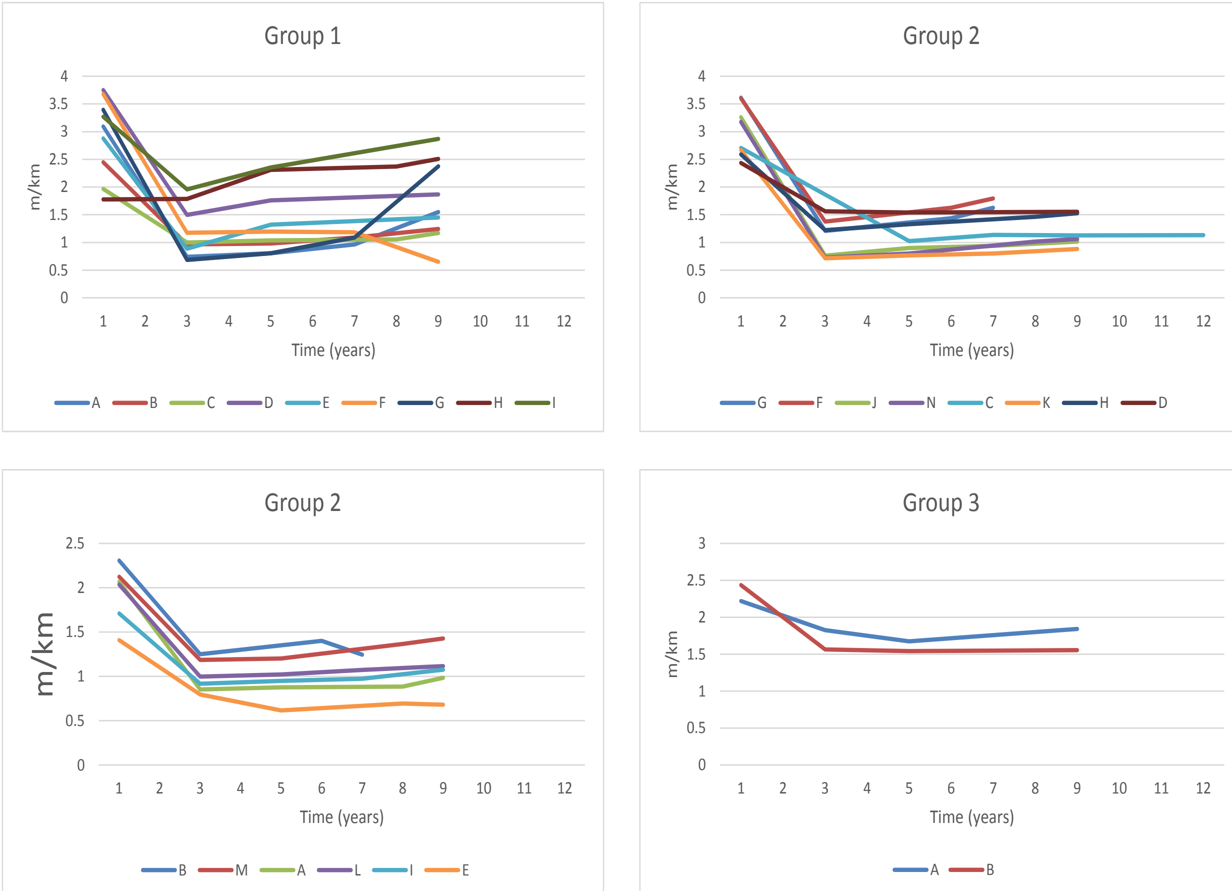


Figure A.16. IRI on the right wheelpath for Groups 1, 2, and 3

APPENDIX B. DISTRESS DETERIORATION PATTERNS FOR HMA RESURFACING WITH MILLING ON COMPOSITE PAVEMENTS

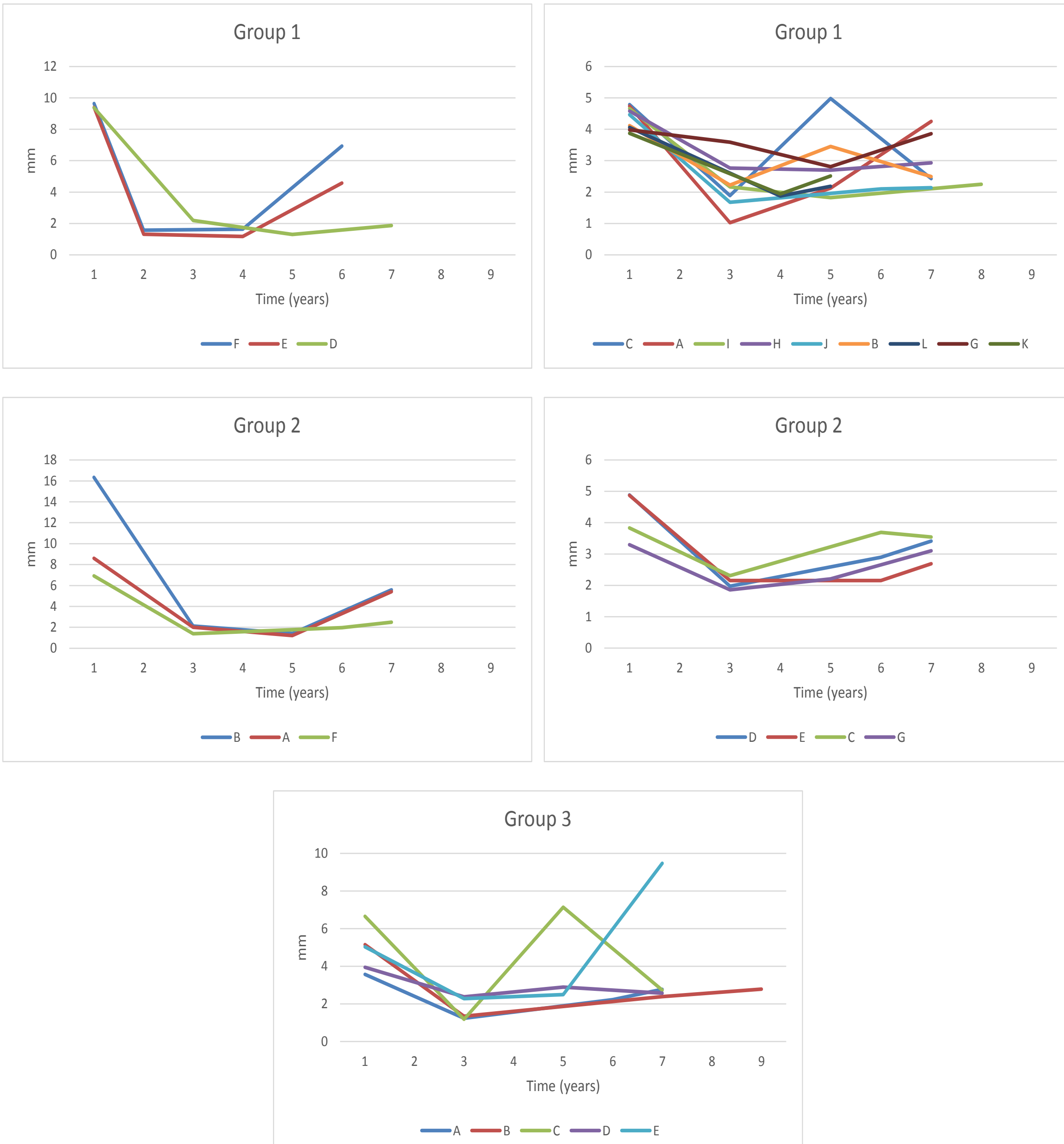


Figure B.1. Rutting on the right wheelpath for Groups 1, 2, and 3

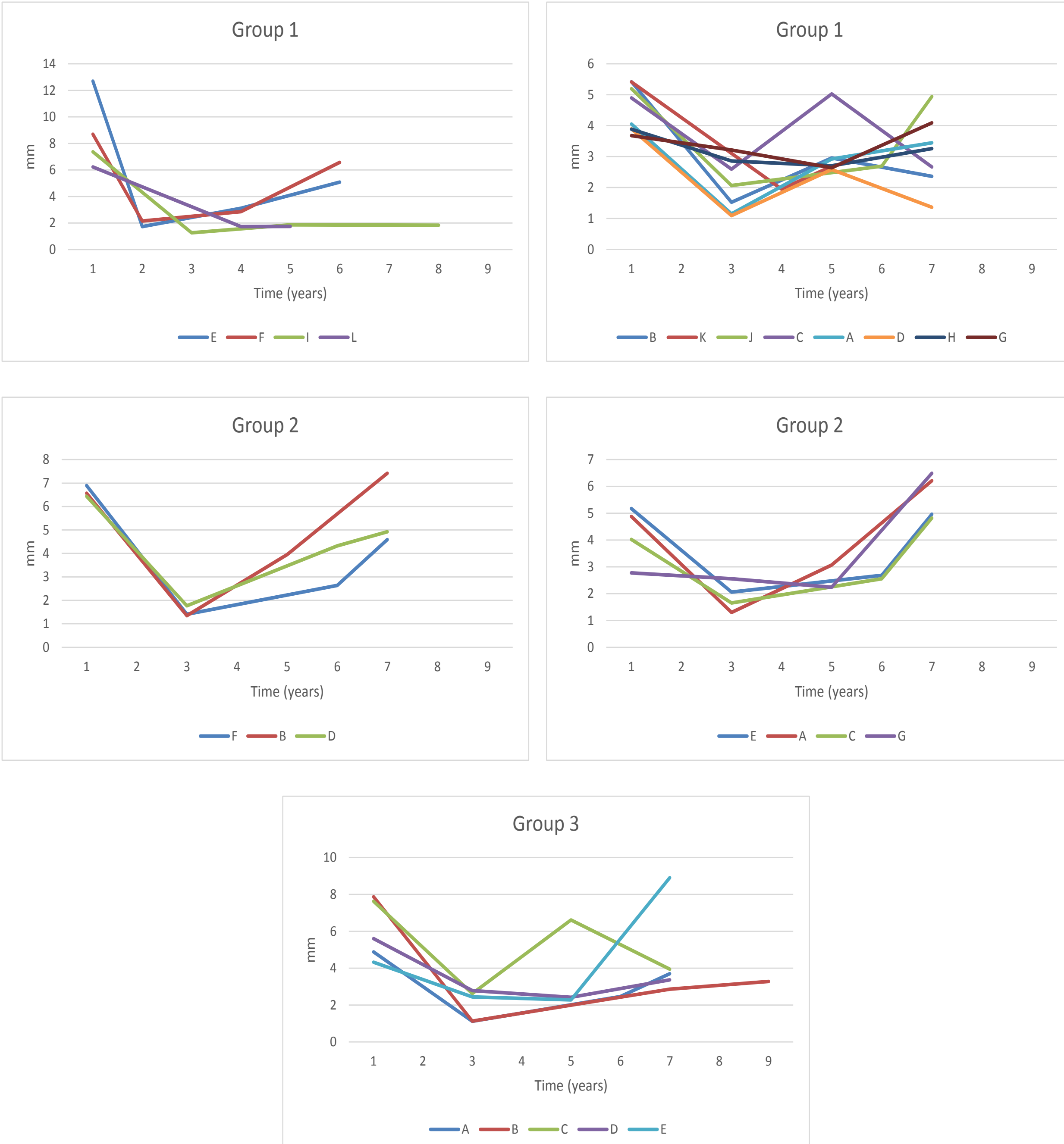


Figure B.2. Rutting on the right wheelpath for Groups 1, 2, and 3

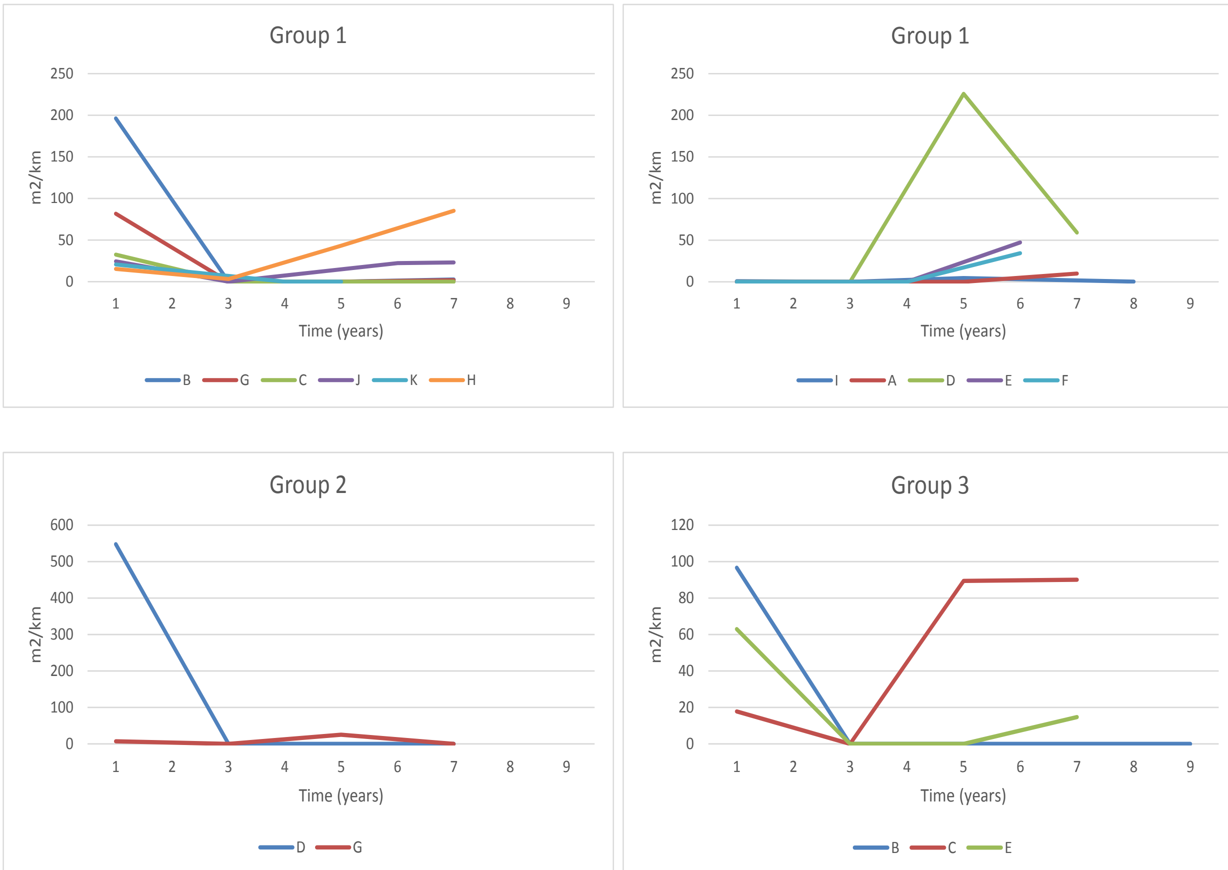


Figure B.3. Moderate severity alligator cracking for Groups 1, 2, and 3

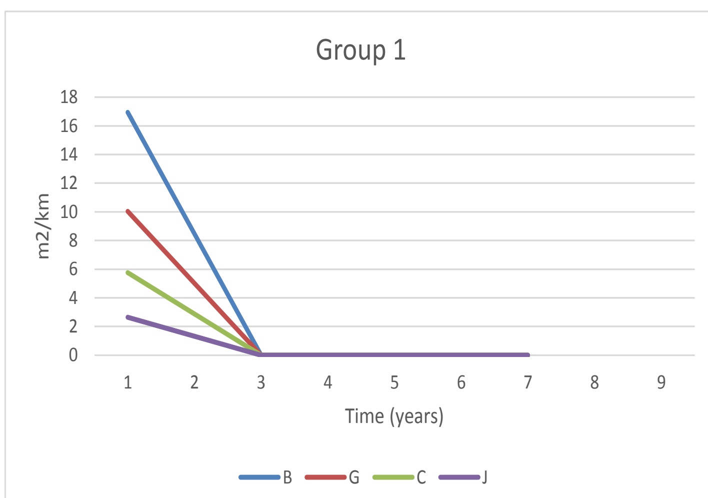


Figure B.4. High severity alligator cracking for Group 1

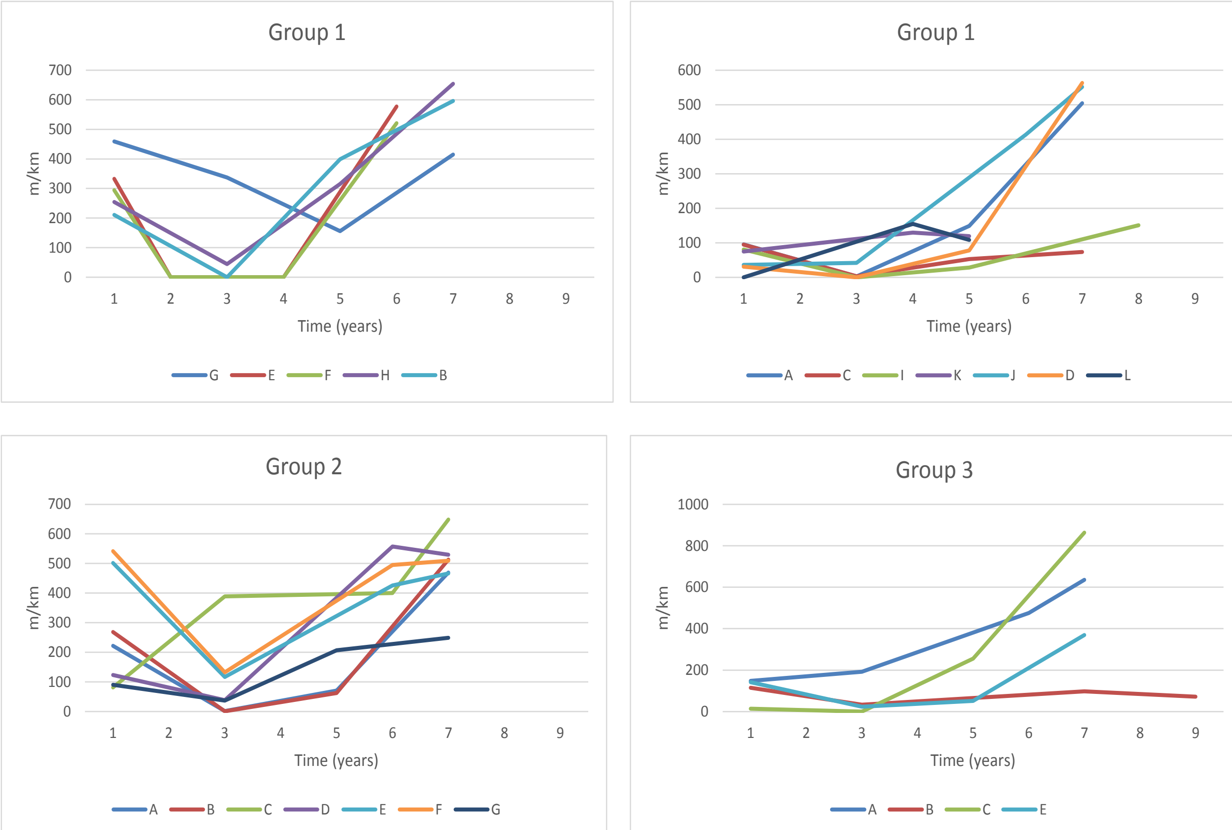


Figure B.5. Low severity transverse cracking for Groups 1, 2, and 3

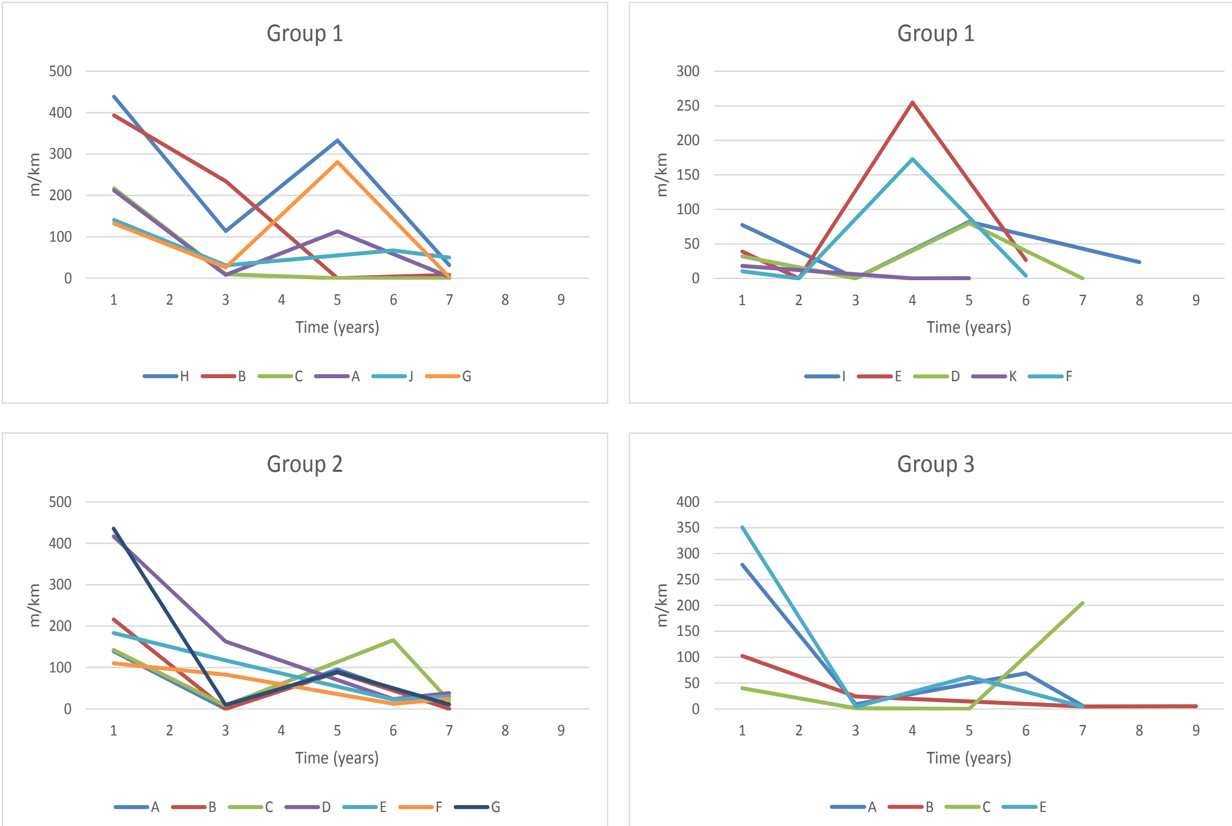


Figure B.6. Moderate severity transverse cracking for Groups 1, 2, and 3

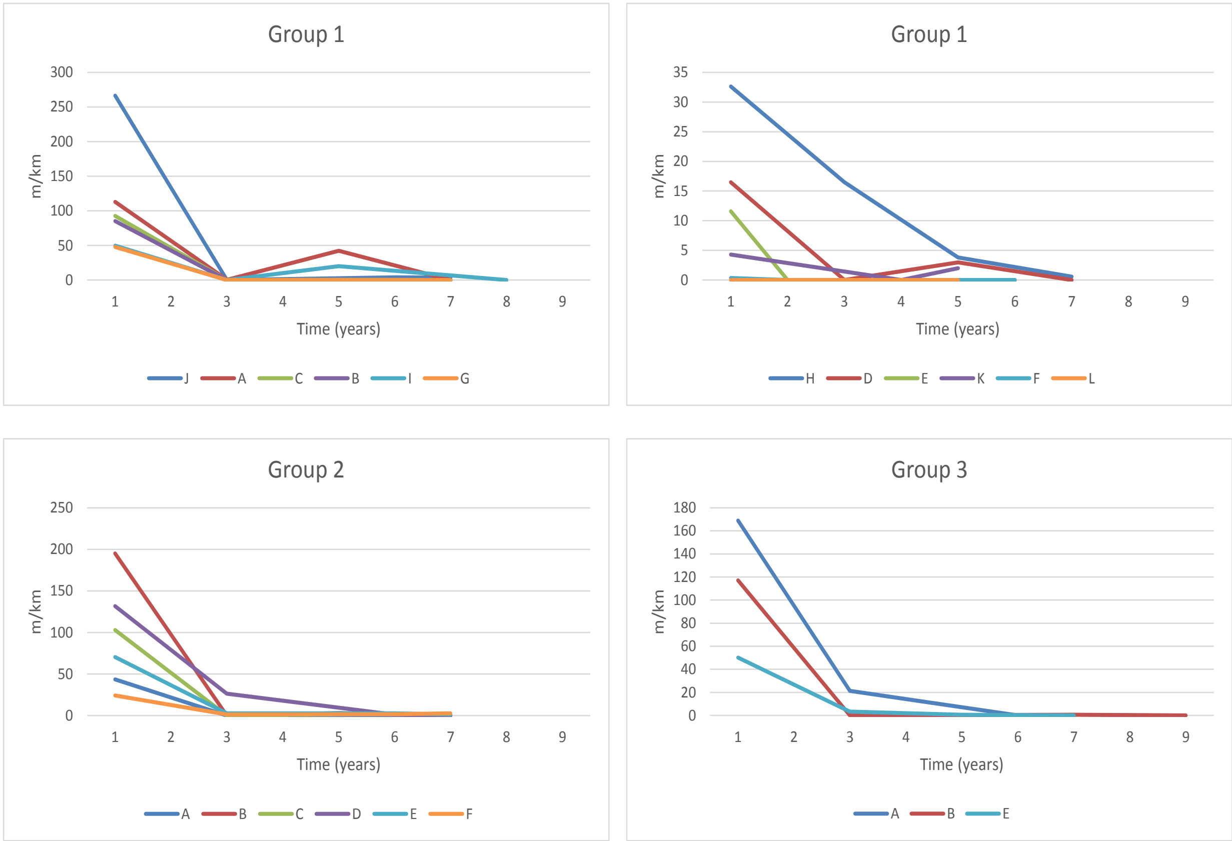


Figure B.7. High severity transverse cracking for Groups 1, 2, and 3

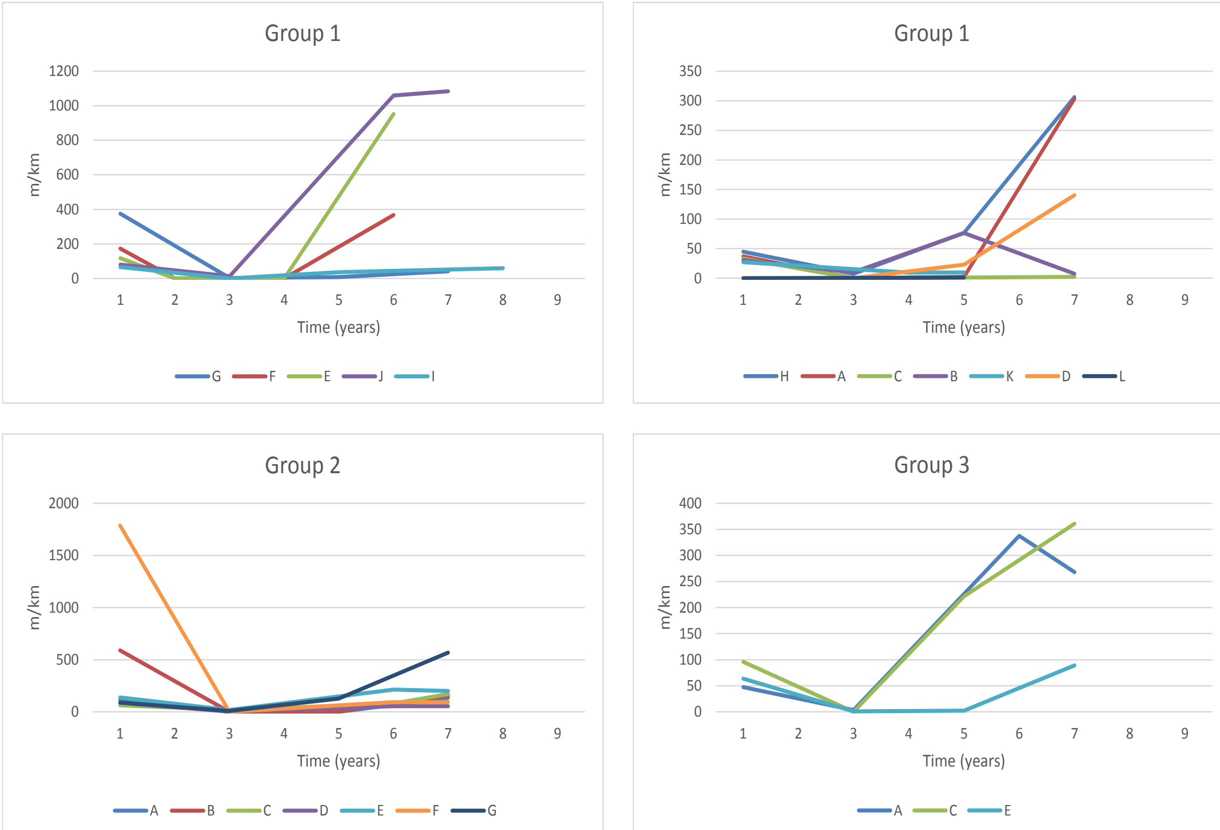


Figure B.8. Low severity longitudinal cracking for Groups 1, 2, and 3

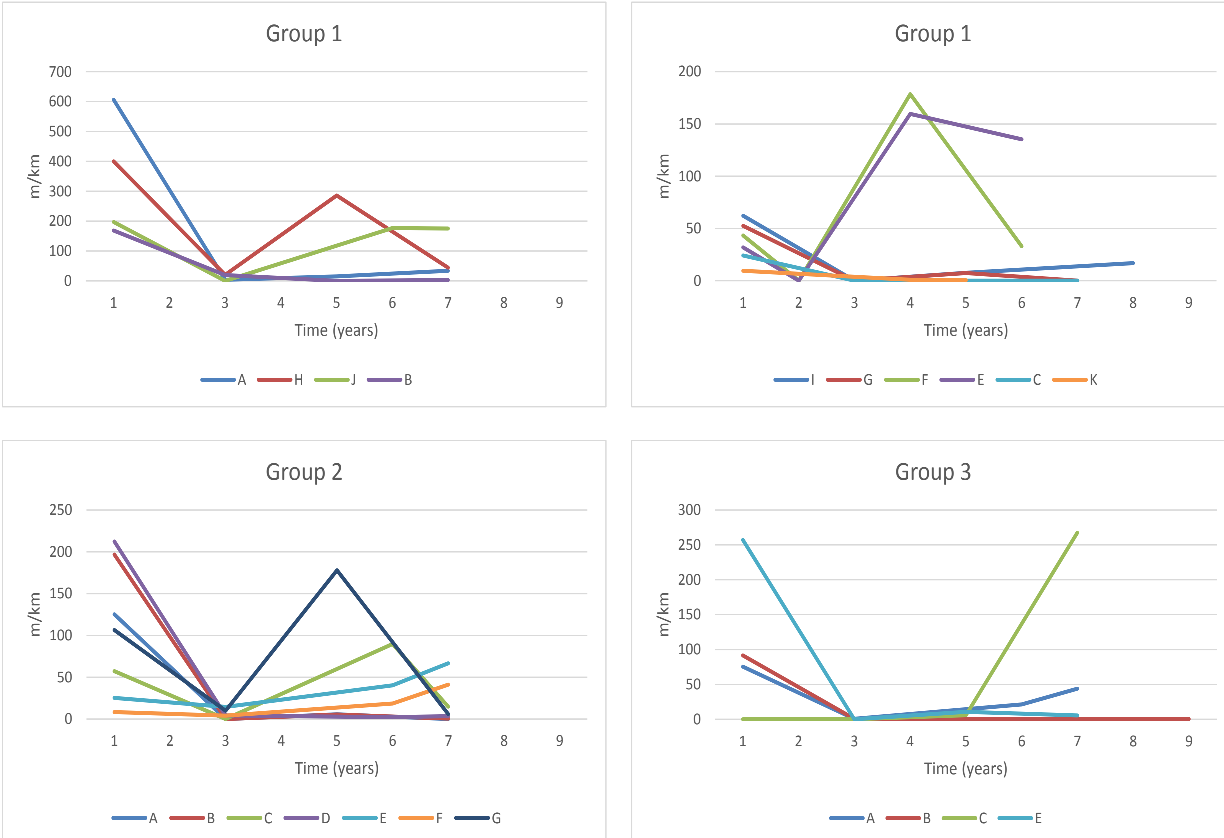


Figure B.9. Moderate severity longitudinal cracking for Groups 1, 2, and 3

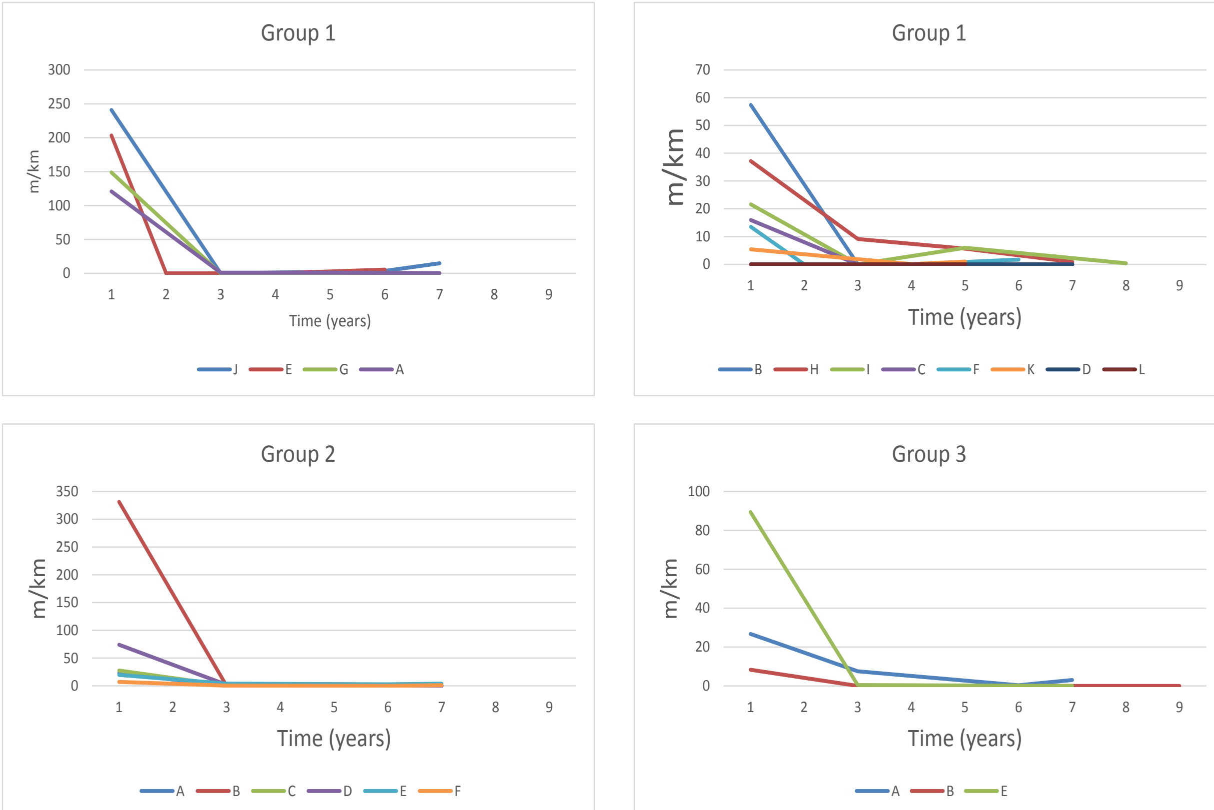


Figure B.10. High severity longitudinal cracking for Groups 1, 2, and 3

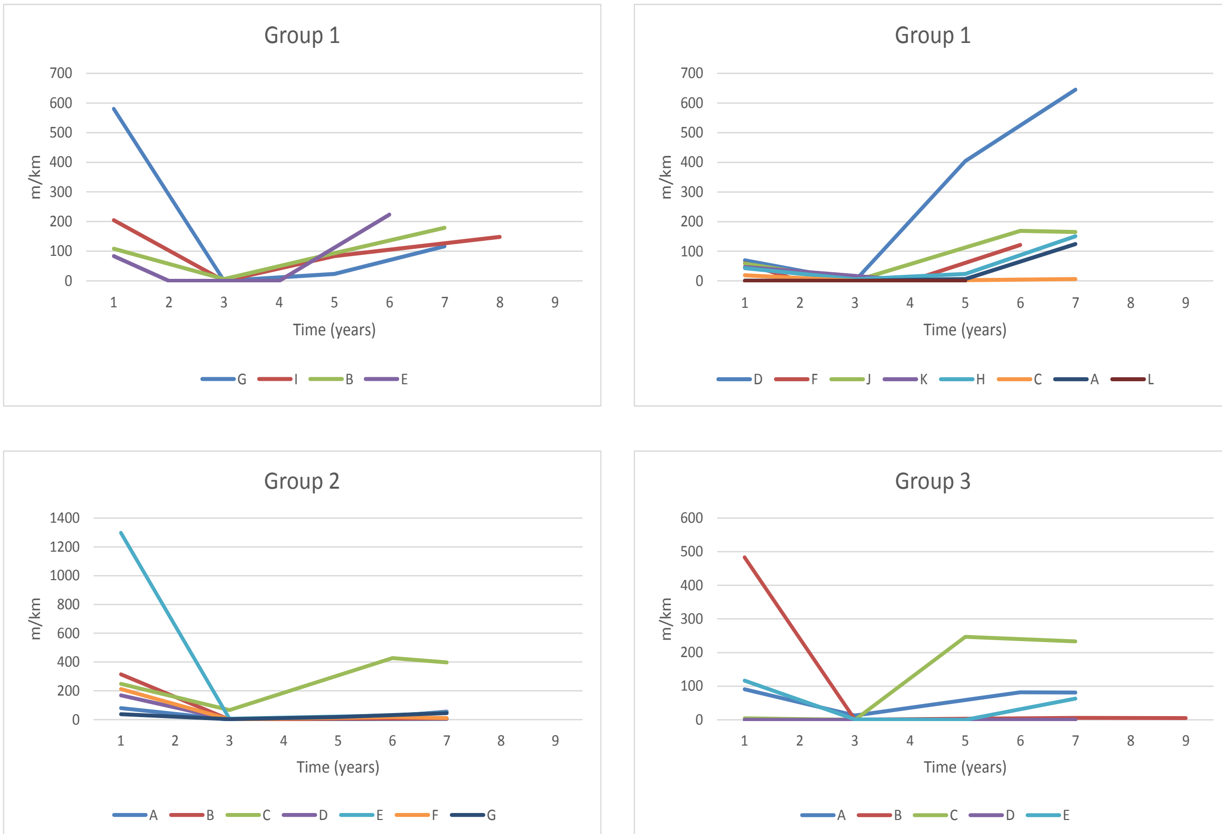


Figure B.11 Low severity longitudinal cracking on wheelpath for Groups 1, 2, and 3

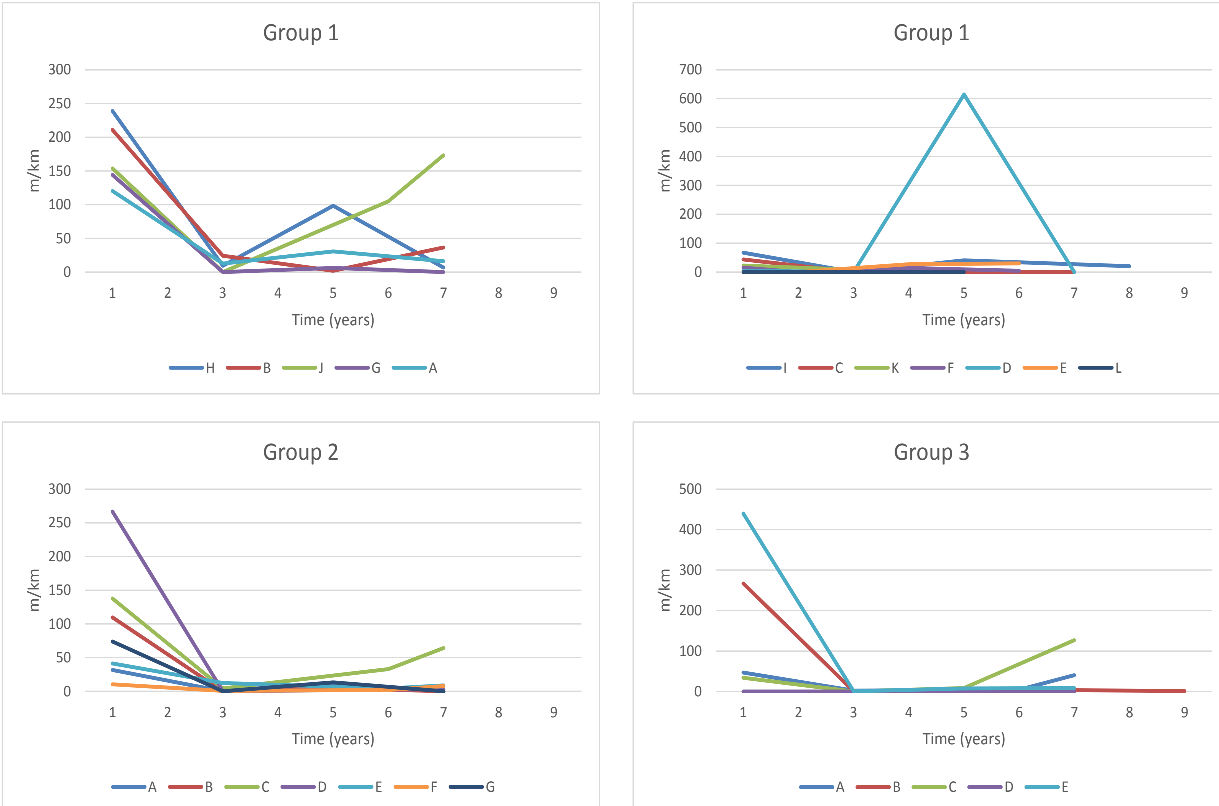


Figure B.12. Moderate severity longitudinal cracking on wheelpath for Groups 1, 2, and 3

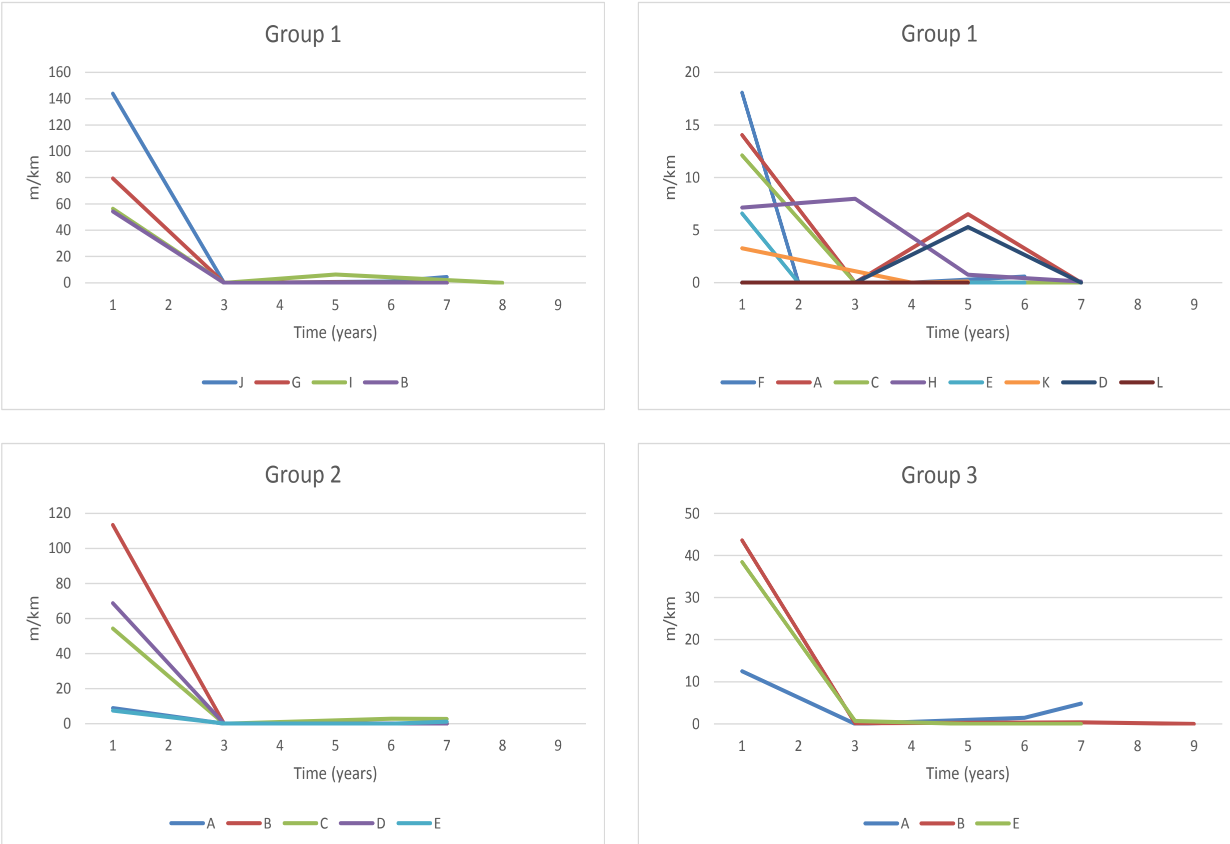


Figure B.13. High severity longitudinal cracking on wheelpath for Groups 1, 2, and 3

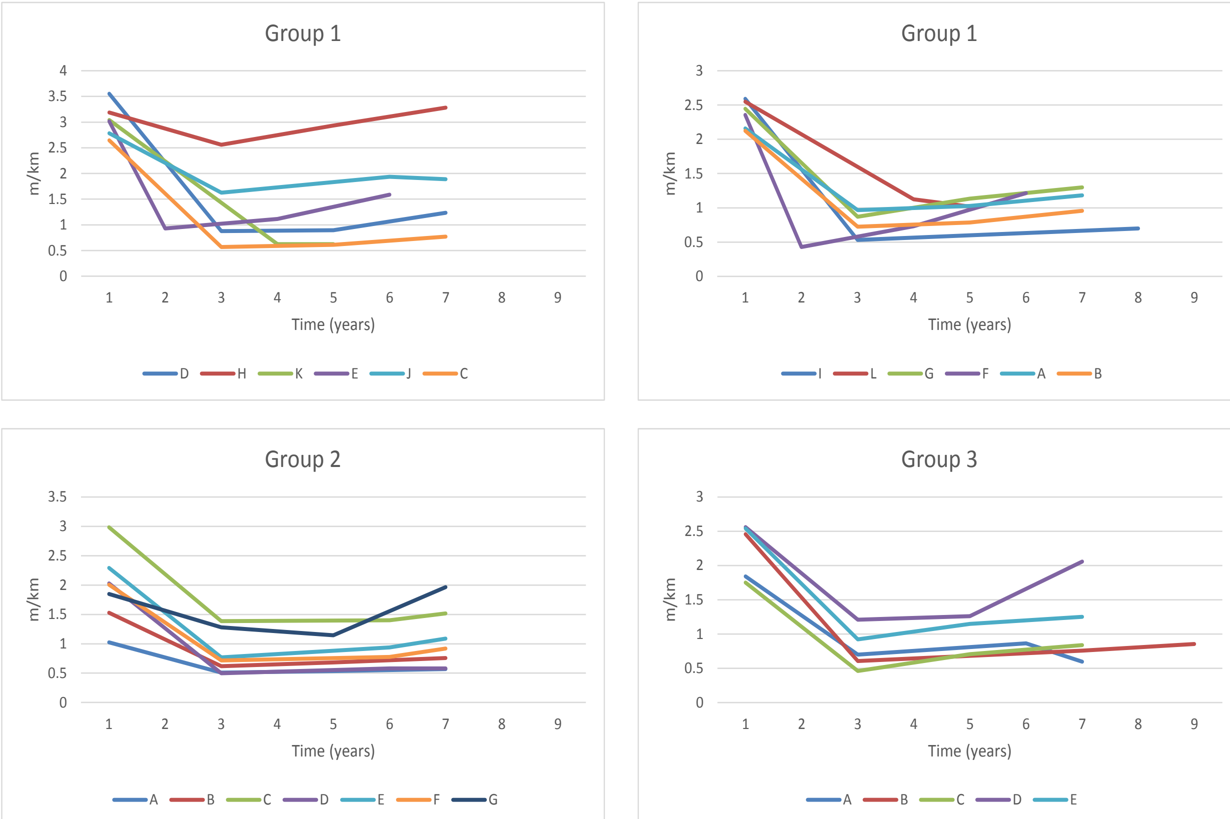


Figure B.14. IRI on the left wheelpath for Groups 1, 2, and 3

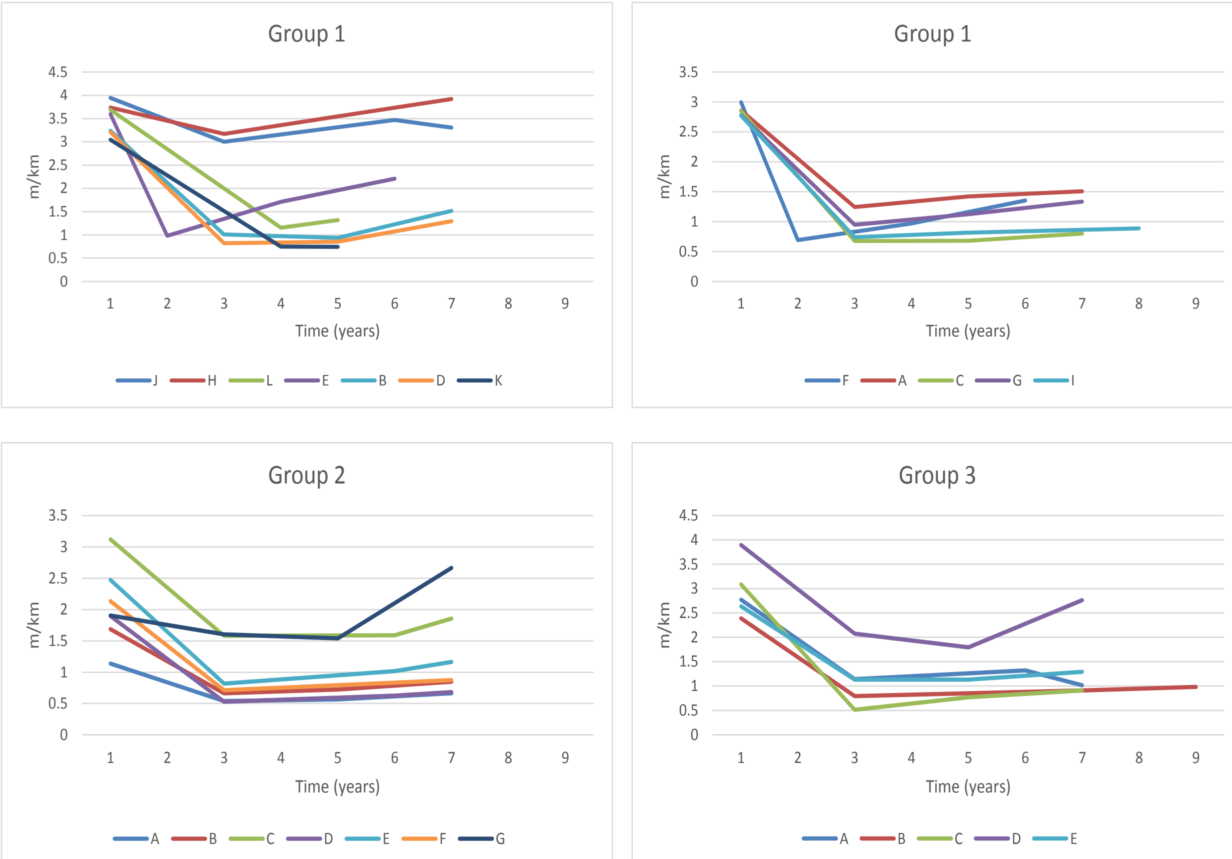


Figure B.15. IRI on the right wheelpath for Groups 1, 2, and 3

APPENDIX C. DISTRESS DETERIORATION PATTERNS FOR HMA RESURFACING WITH CIPR

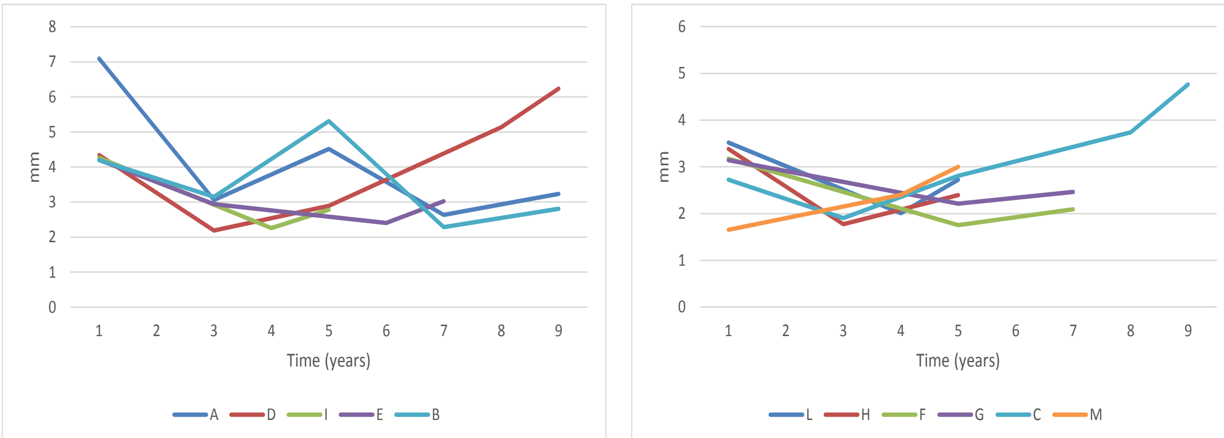


Figure C.1. Rutting on the left wheelpath

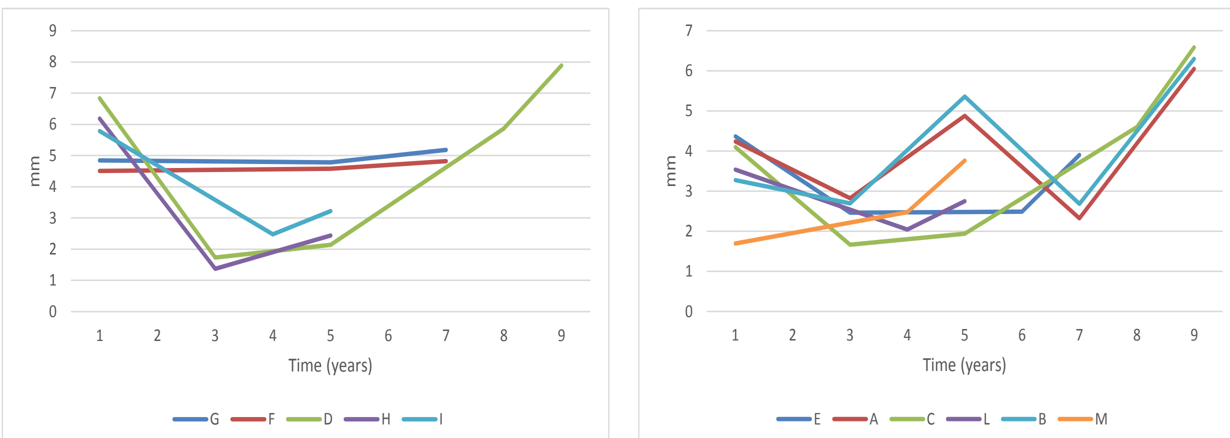


Figure C.2. Rutting on the right wheelpath

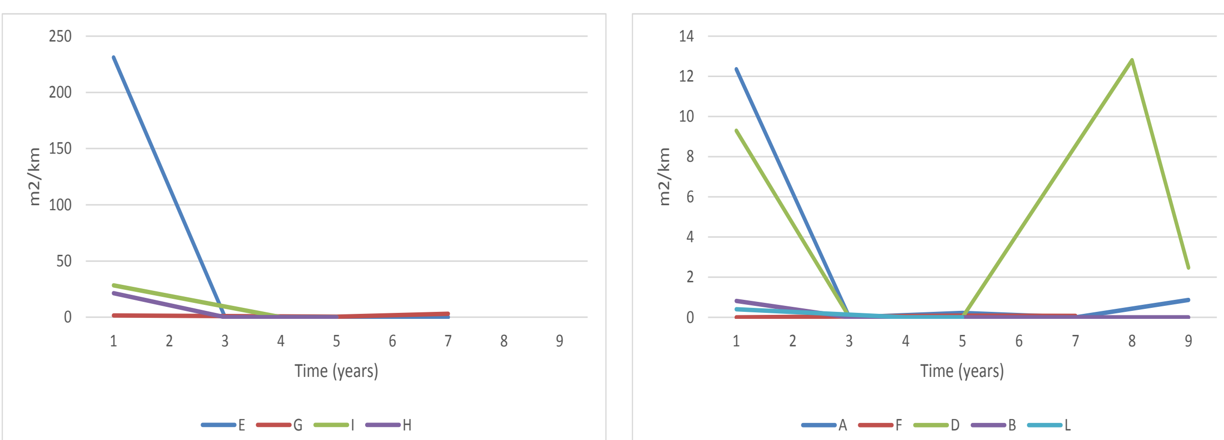


Figure C.3. Moderate alligator cracking

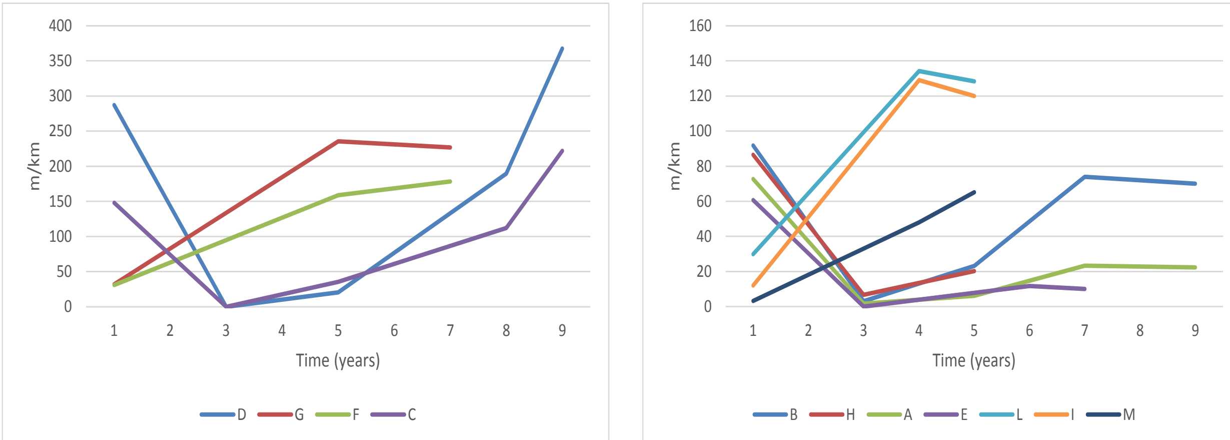


Figure C.5. Low severity transverse cracking

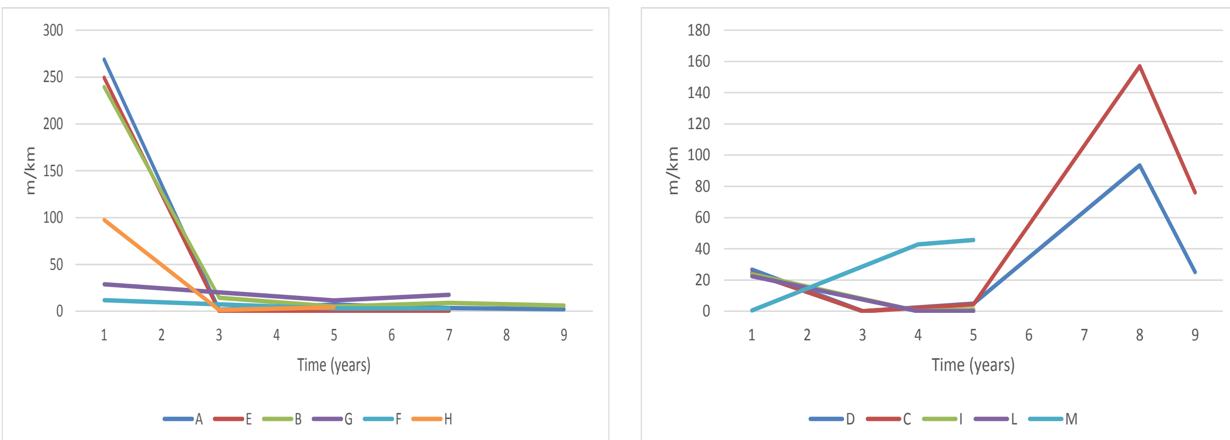


Figure C.6. Moderate severity transverse cracking

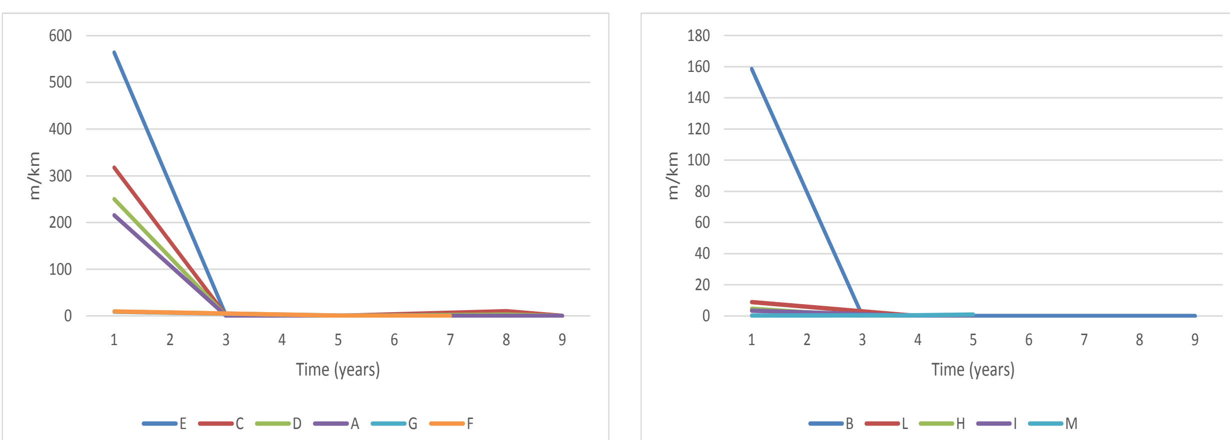


Figure C.7. High severity transverse cracking

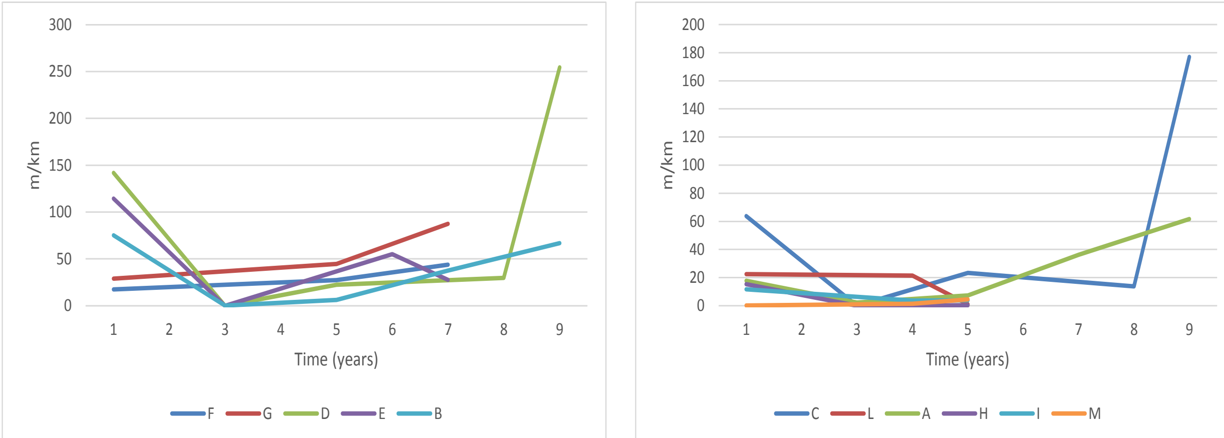


Figure C.8. Low severity longitudinal cracking

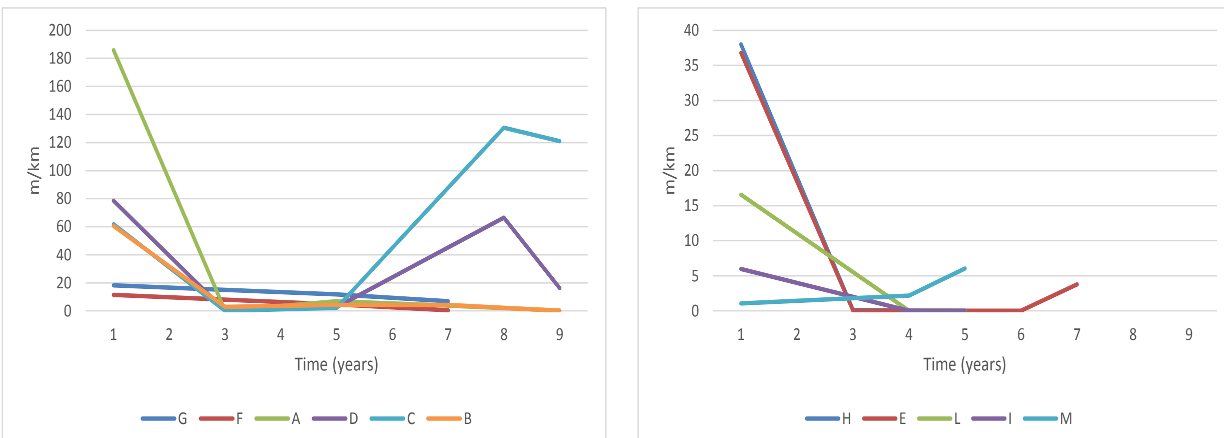


Figure C.9. Moderate severity longitudinal cracking

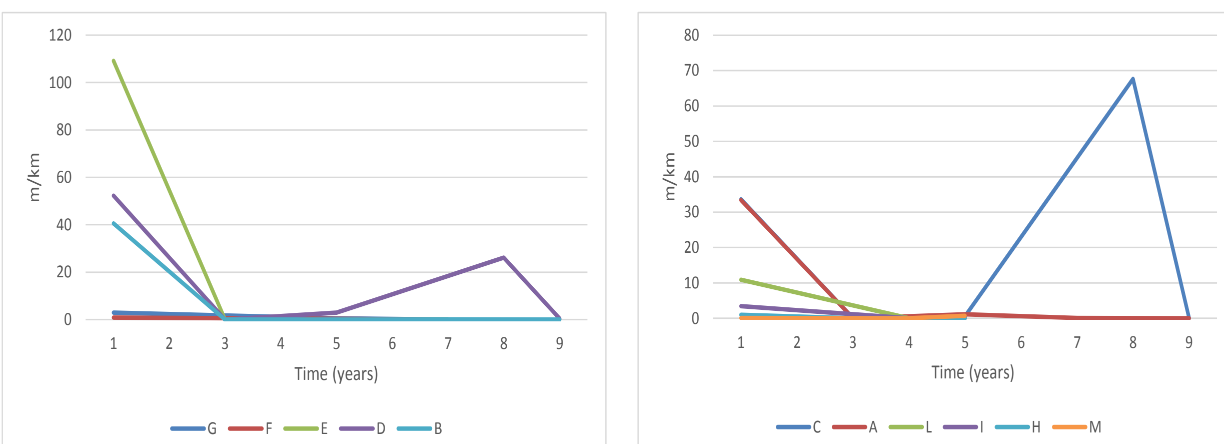


Figure C.10. High severity longitudinal cracking

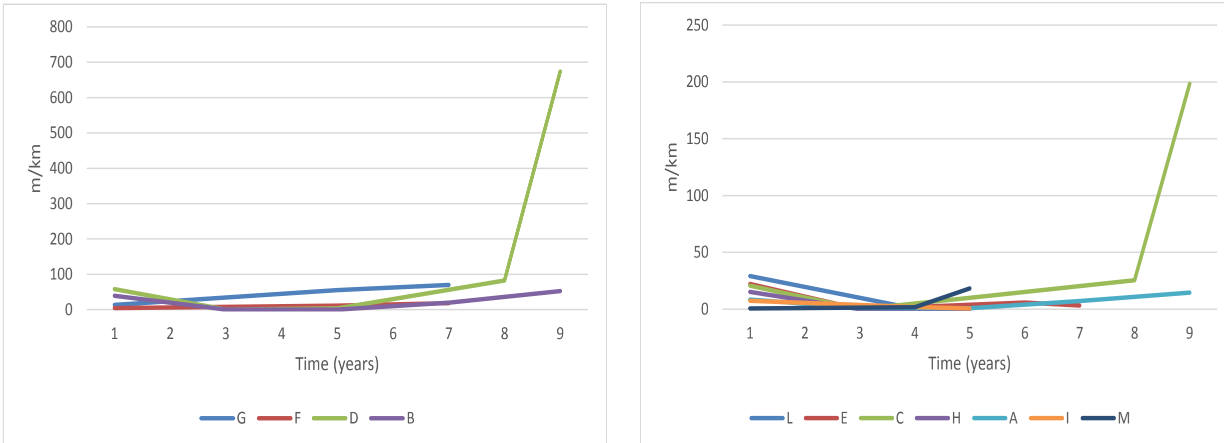


Figure C.11. Low severity longitudinal cracking on wheelpath

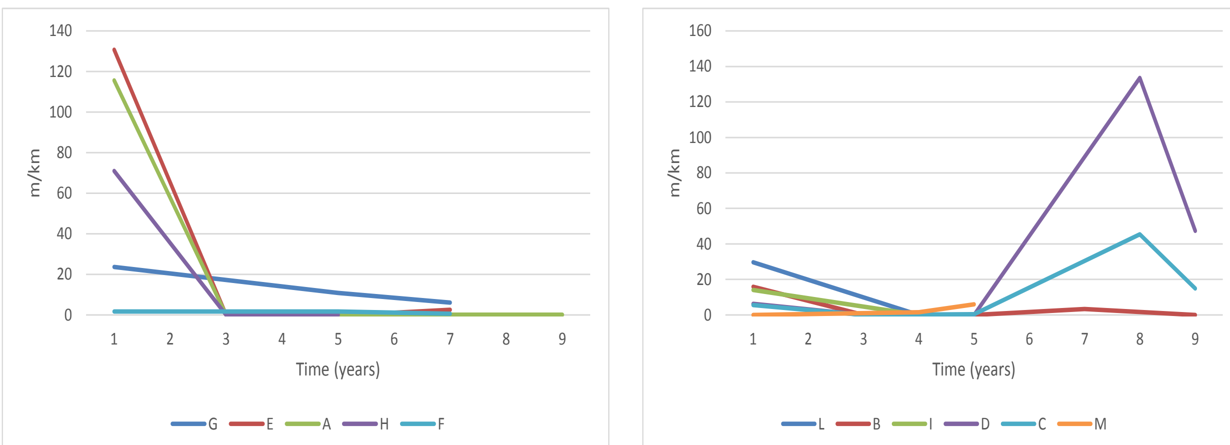


Figure C.12. Moderate severity longitudinal cracking on wheelpath

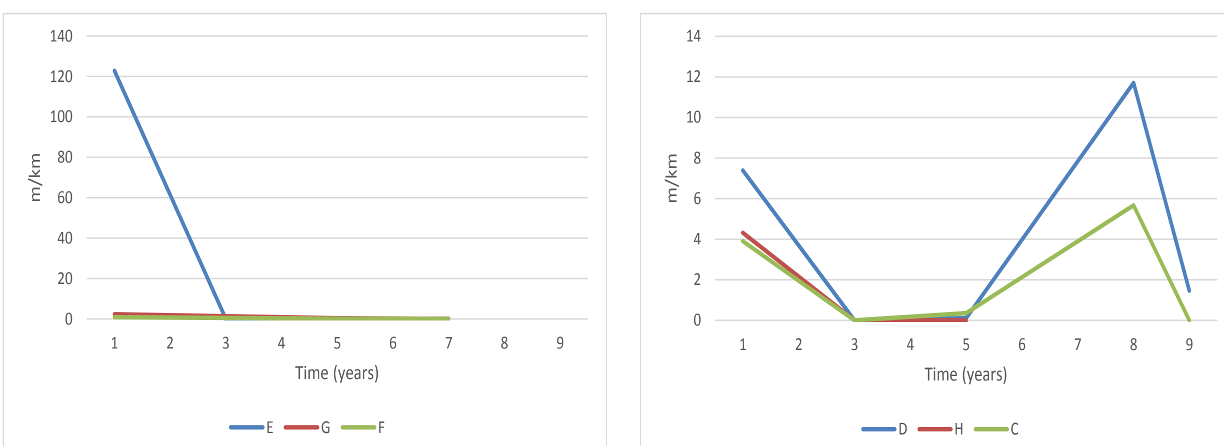


Figure C.13. High severity longitudinal cracking on wheelpath

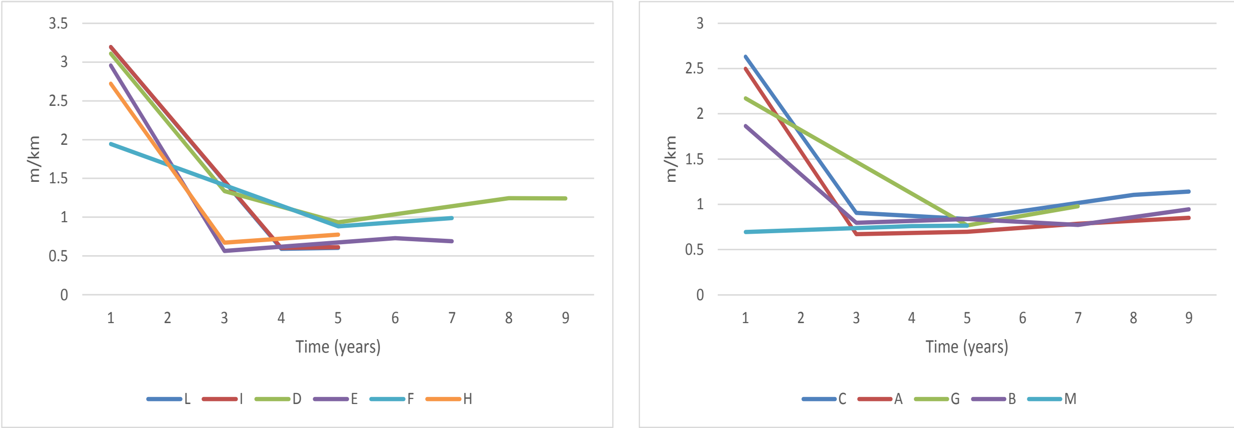


Figure C.14. IRI on the left wheelpath

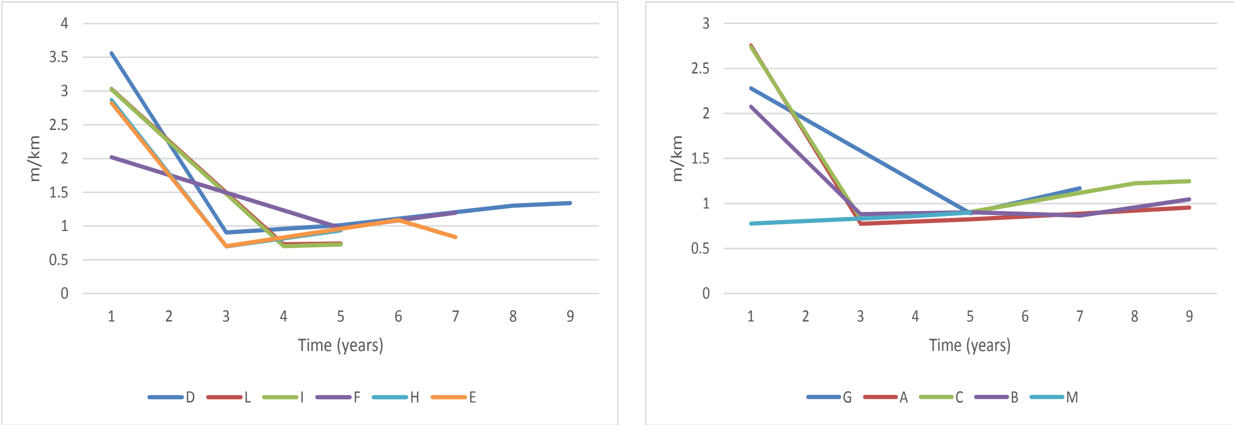


Figure C.15. IRI on the right wheelpath

APPENDIX D. DISTRESS DETERIORATION PATTERNS FOR HMA RESURFACING WITH MILLING

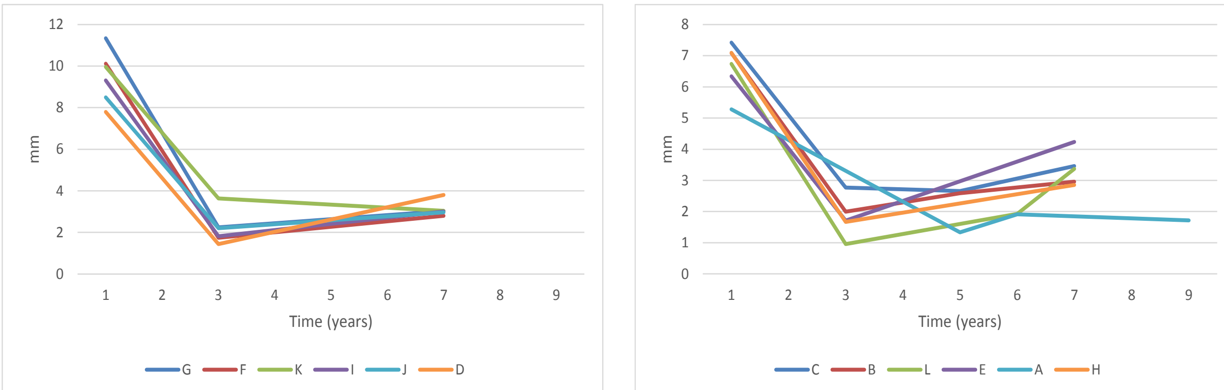


Figure D.1. Rutting on left wheelpath

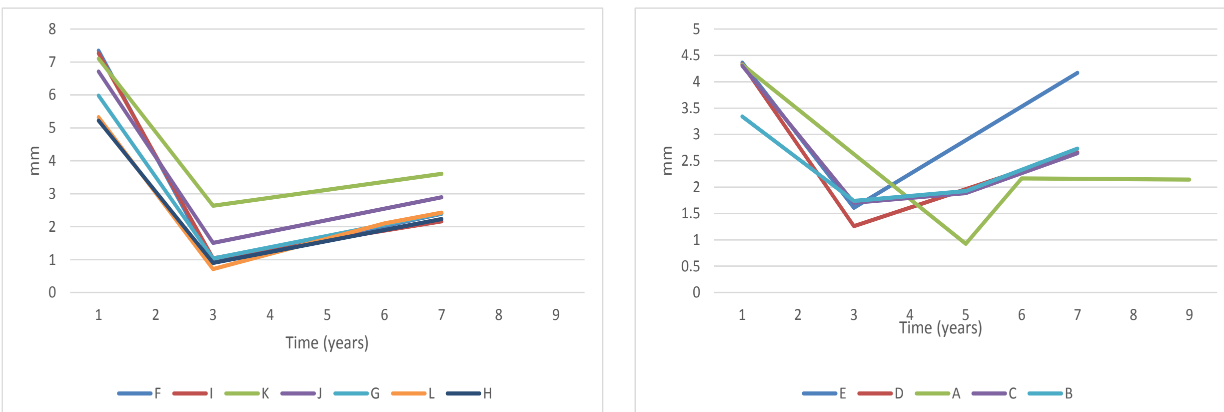


Figure D.2. Rutting on the right wheelpath

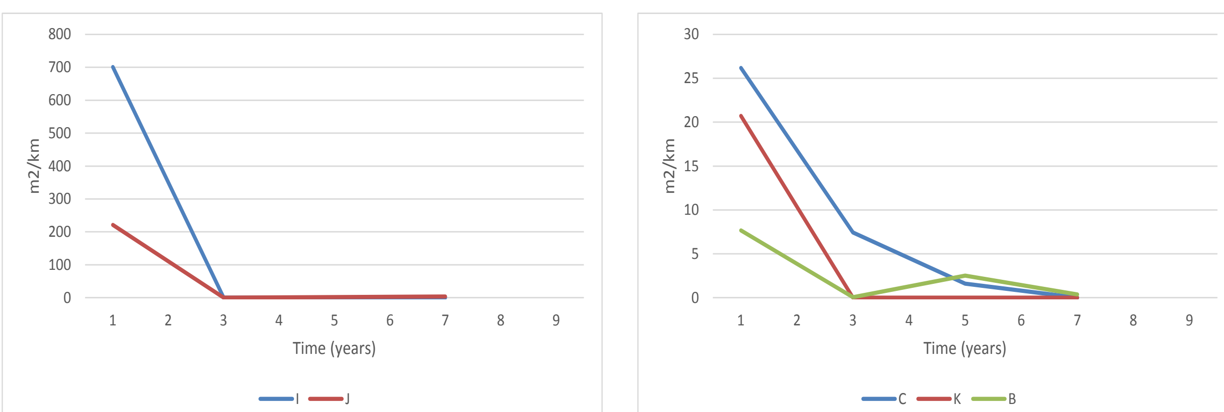


Figure D.3. Moderate alligator cracking

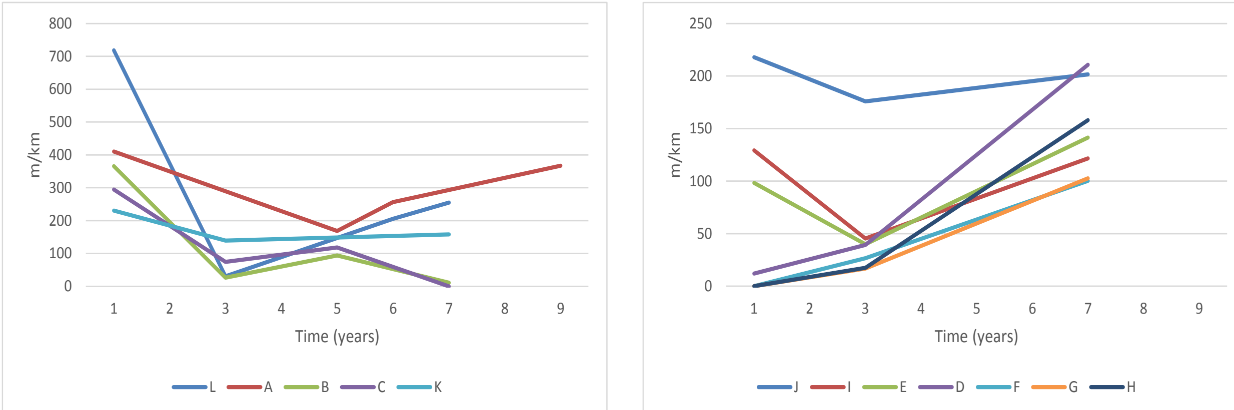


Figure D.4. Low severity transverse cracking

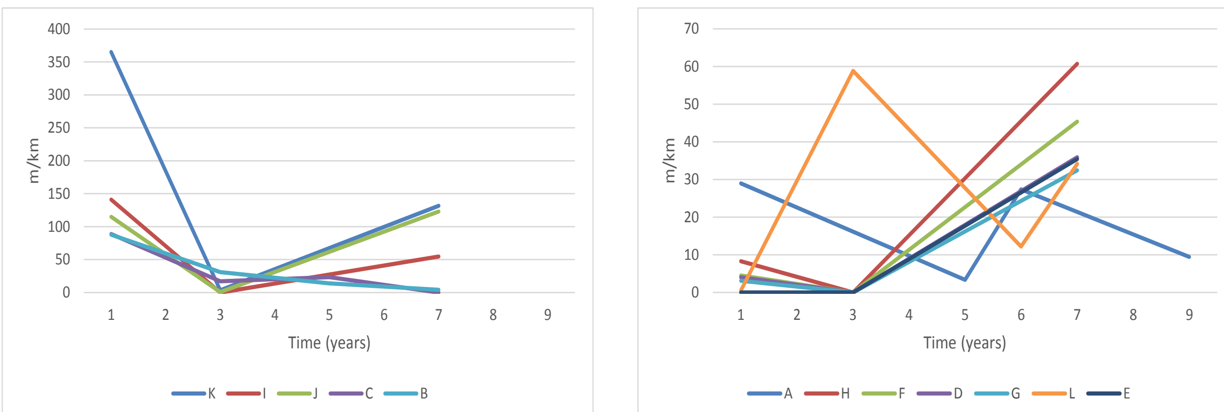


Figure D.5. Moderate severity transverse cracking

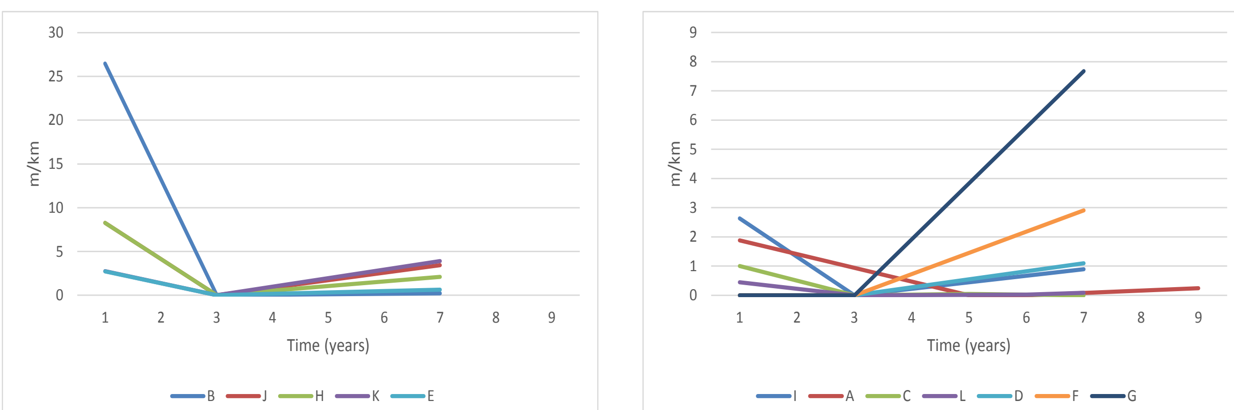


Figure D.6. High severity transverse cracking

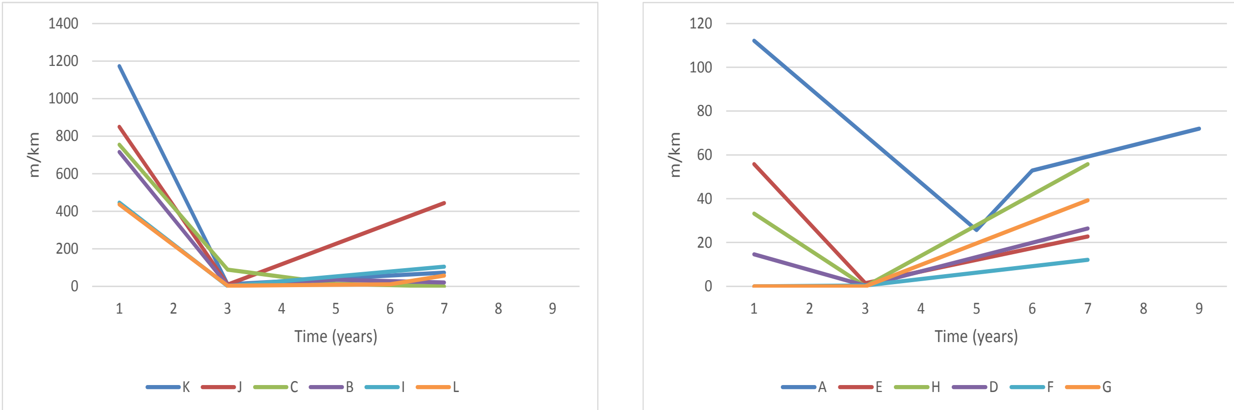


Figure D.7. Low severity longitudinal cracking

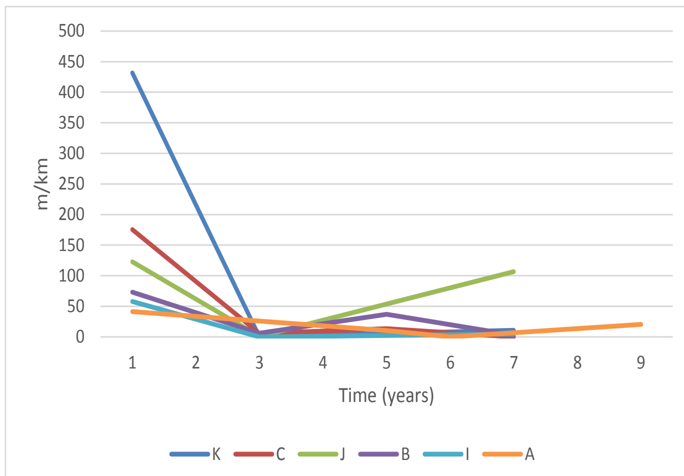


Figure D.8. Moderate severity longitudinal cracking

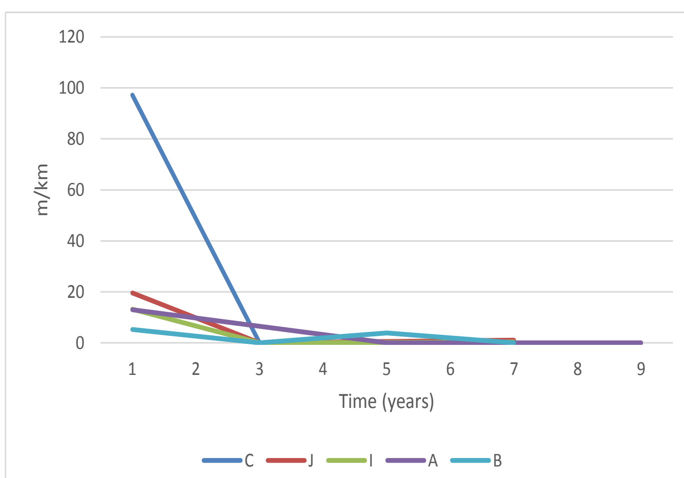


Figure D.9. High severity longitudinal cracking

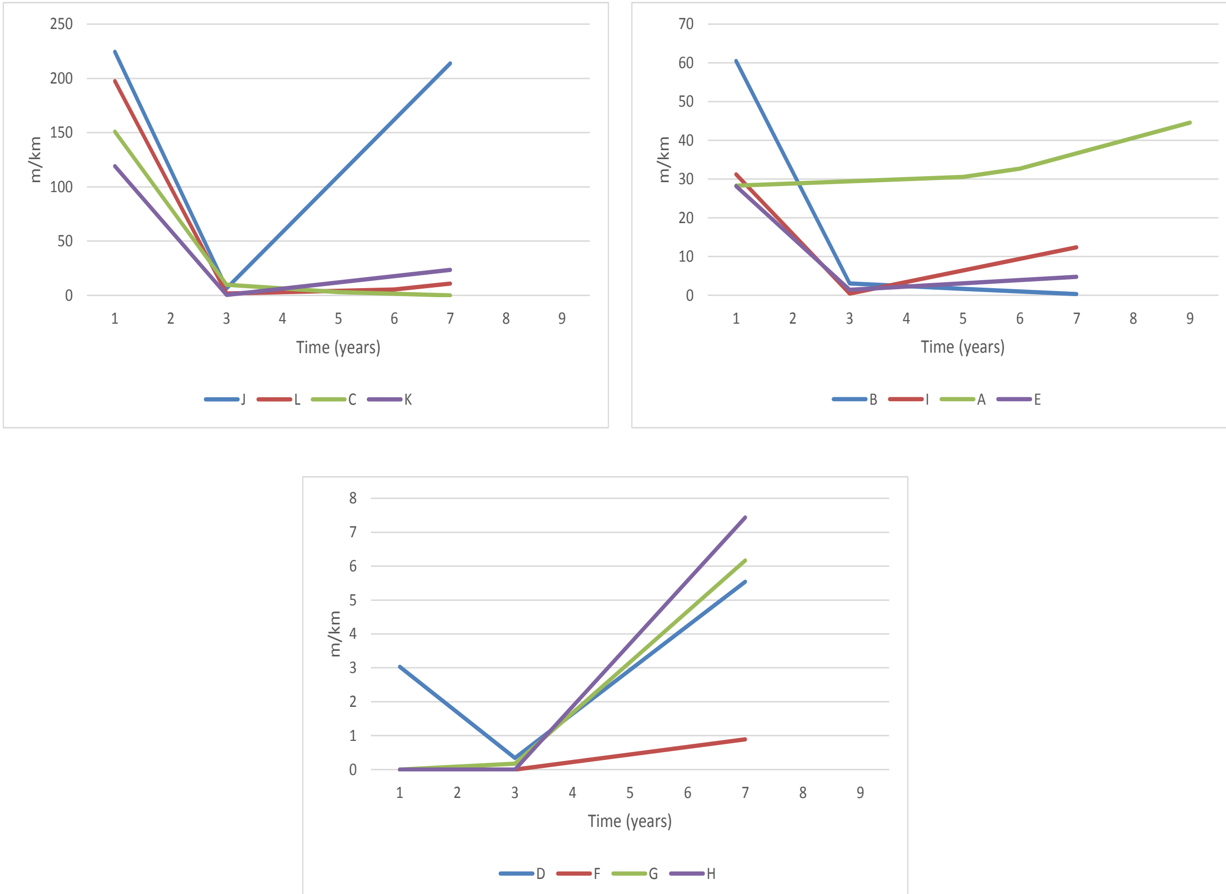


Figure D.10. Low severity longitudinal cracking on wheelpath

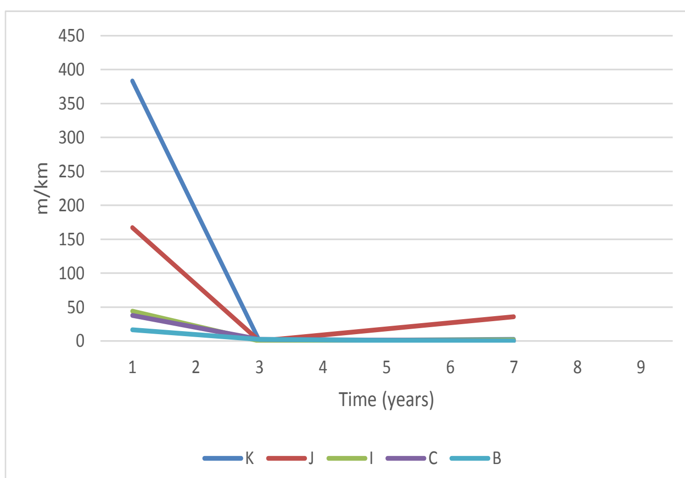


Figure D.11. Moderate severity longitudinal cracking on wheelpath

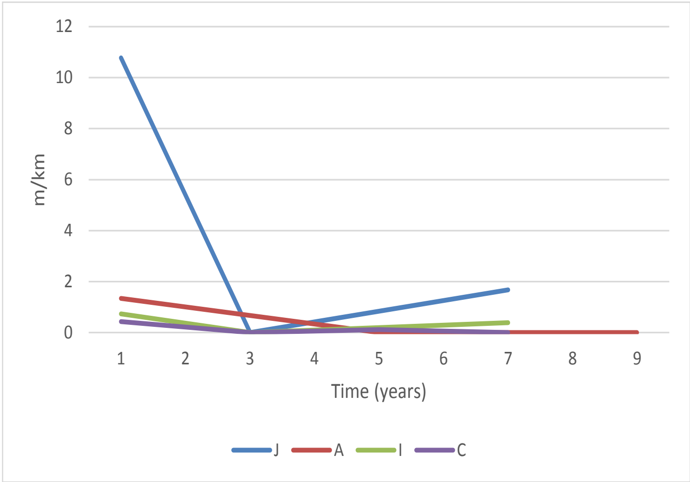
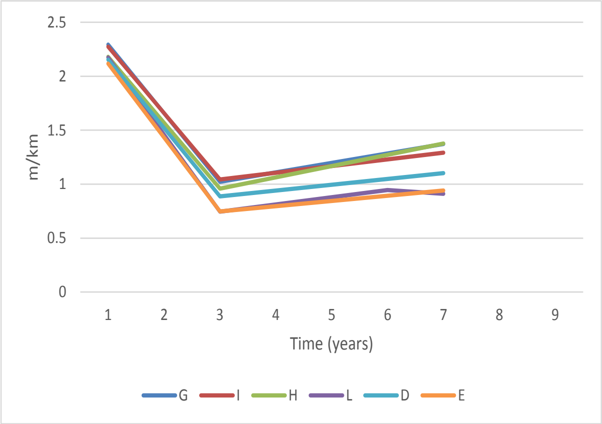


Figure D.12. High severity longitudinal cracking on wheelpath



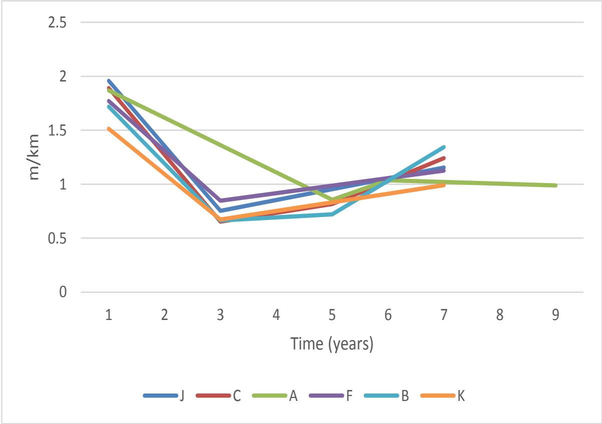
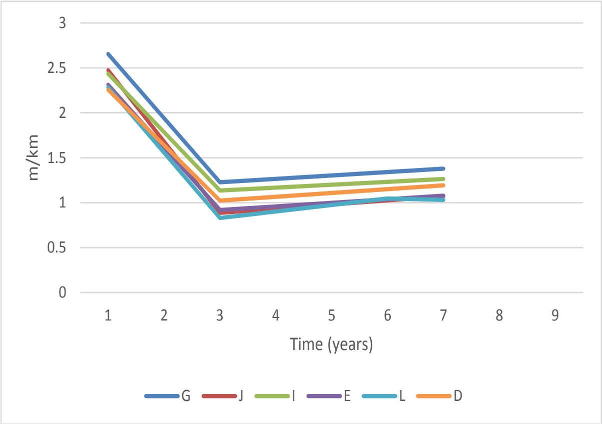


Figure D.13. IRI on the left wheelpath



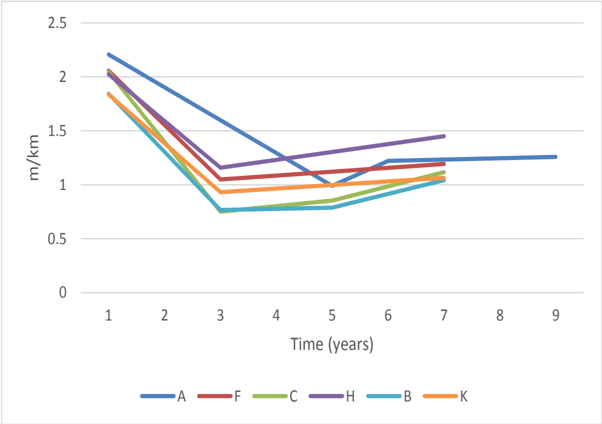


Figure D.14. IRI on the right wheelpath

APPENDIX E. DISTRESS DETERIORATION PATTERNS FOR HMA RESURFACING WITH CIPR ON AC PAVEMENTS

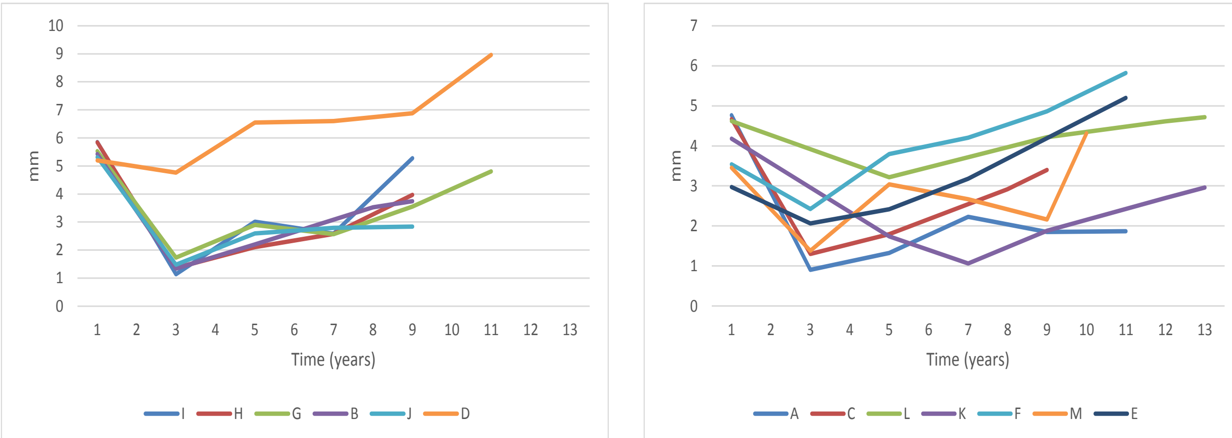


Figure E.1. Rutting deterioration on right wheelpath

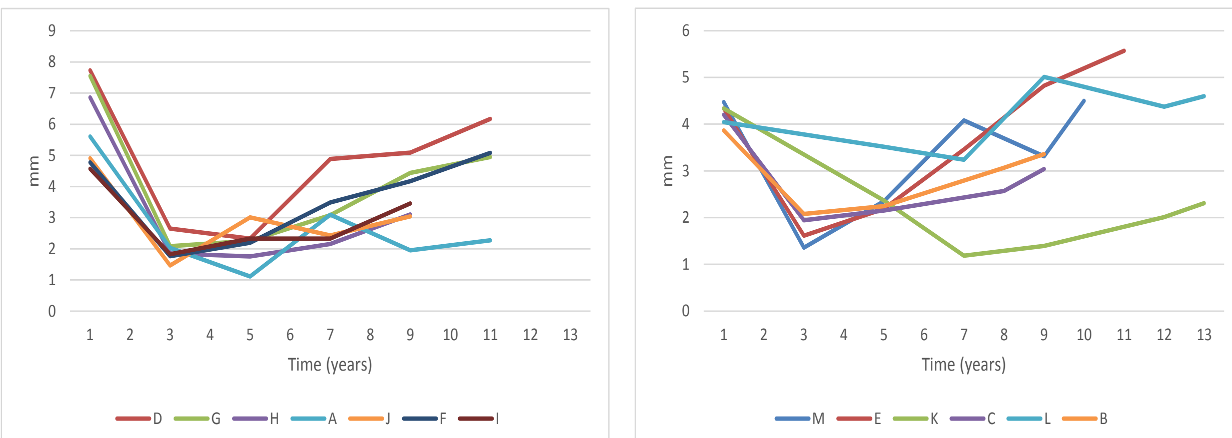


Figure E.2. Rutting deterioration on left wheelpath

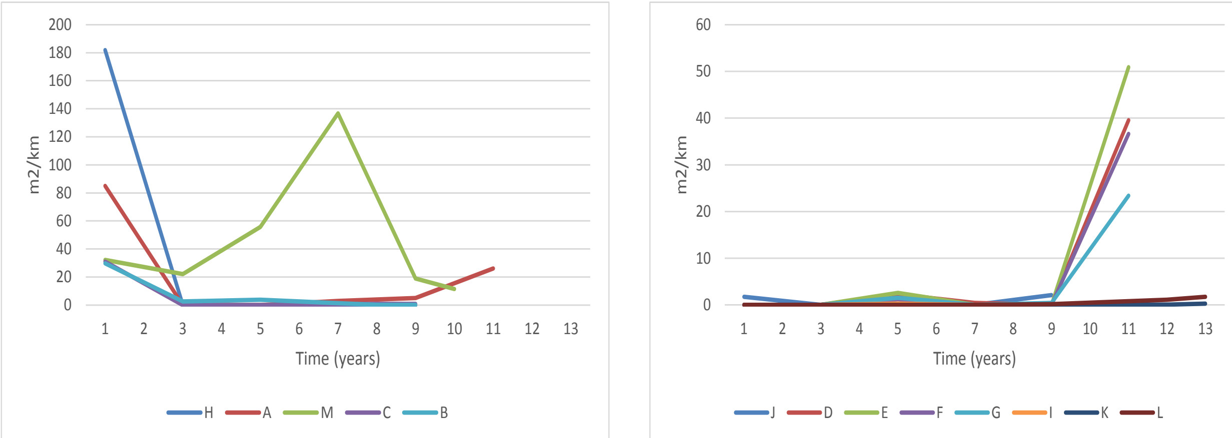


Figure E.3. Moderate alligator cracking deterioration

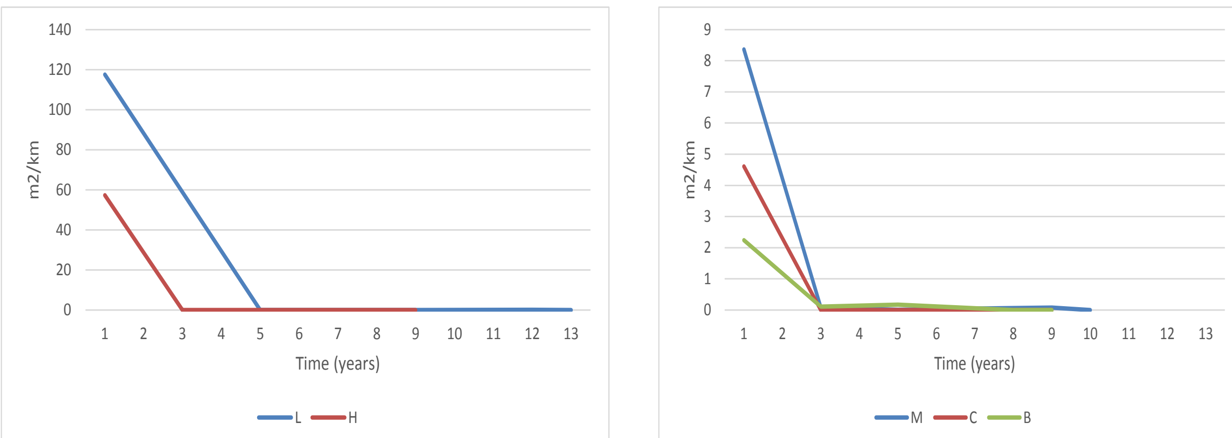


Figure E.4. High alligator cracking

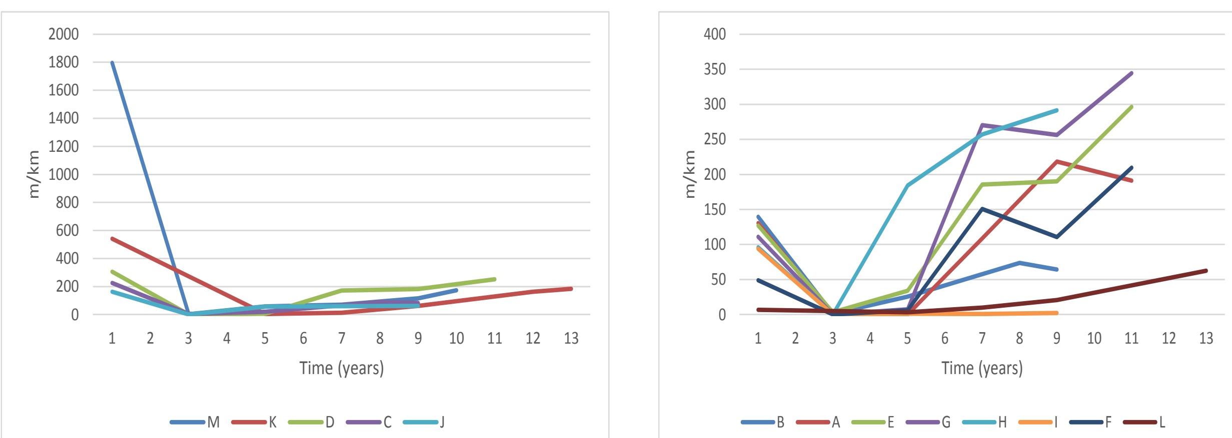


Figure E.5. Low transverse cracking

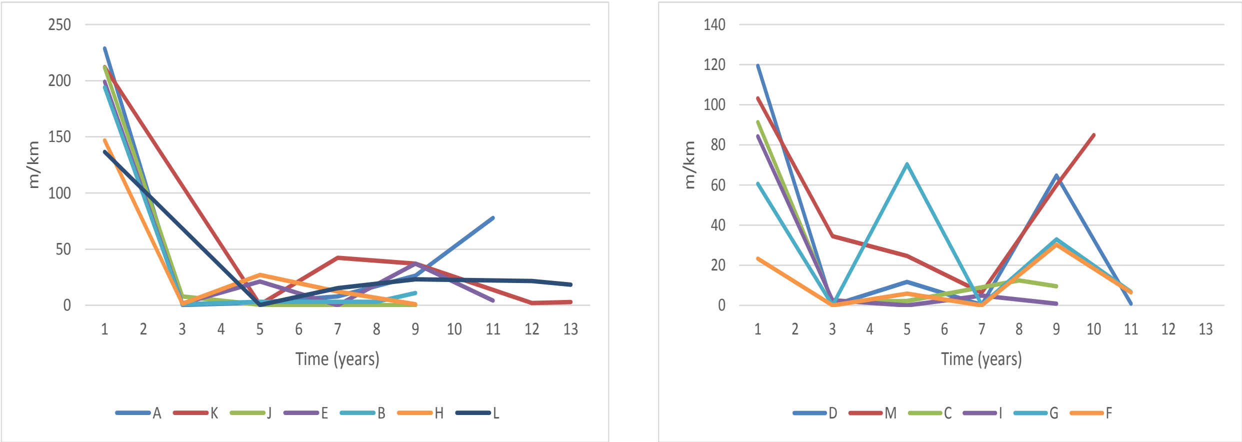


Figure E.6. Moderate transverse cracking

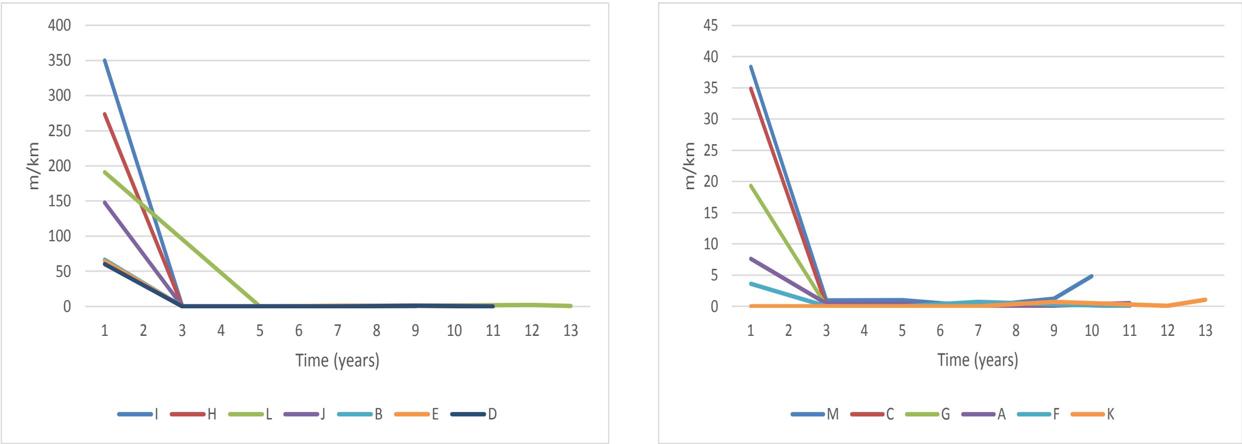


Figure E.7. High transverse cracking

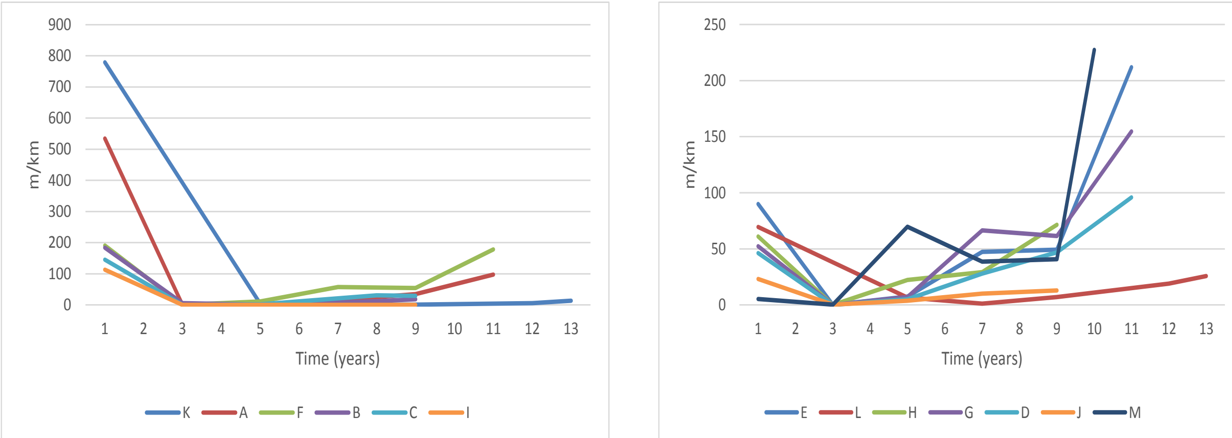


Figure E.8. Low longitudinal cracking

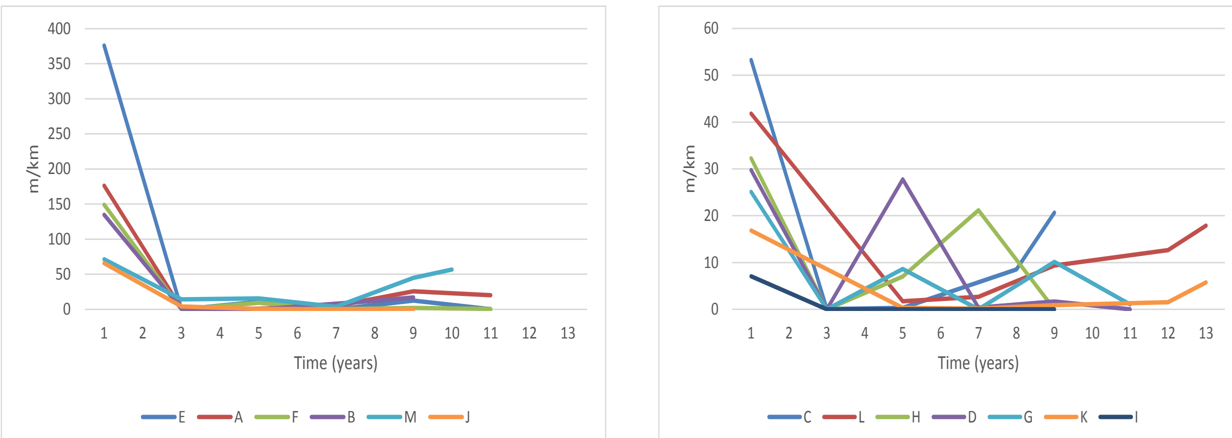


Figure E.9. Moderate longitudinal cracking

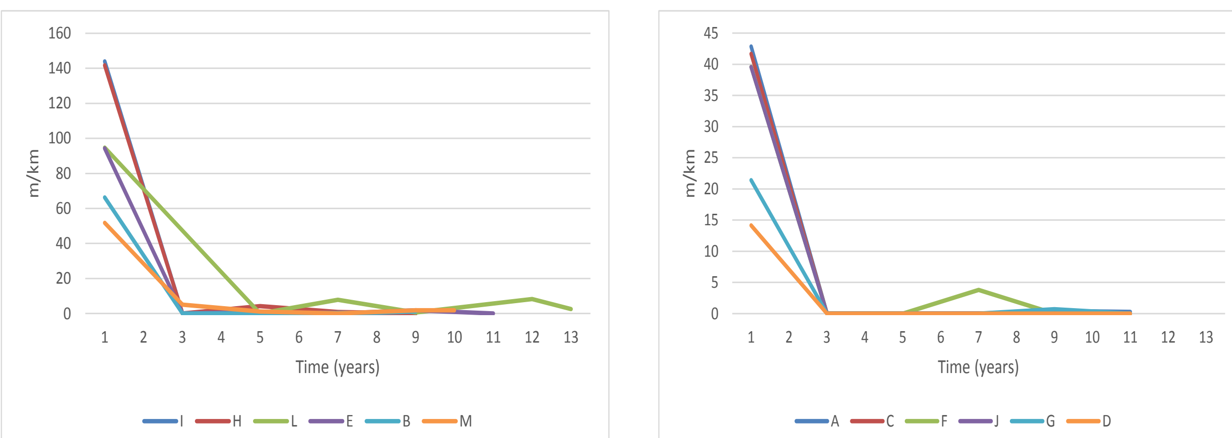


Figure E.10. High longitudinal cracking

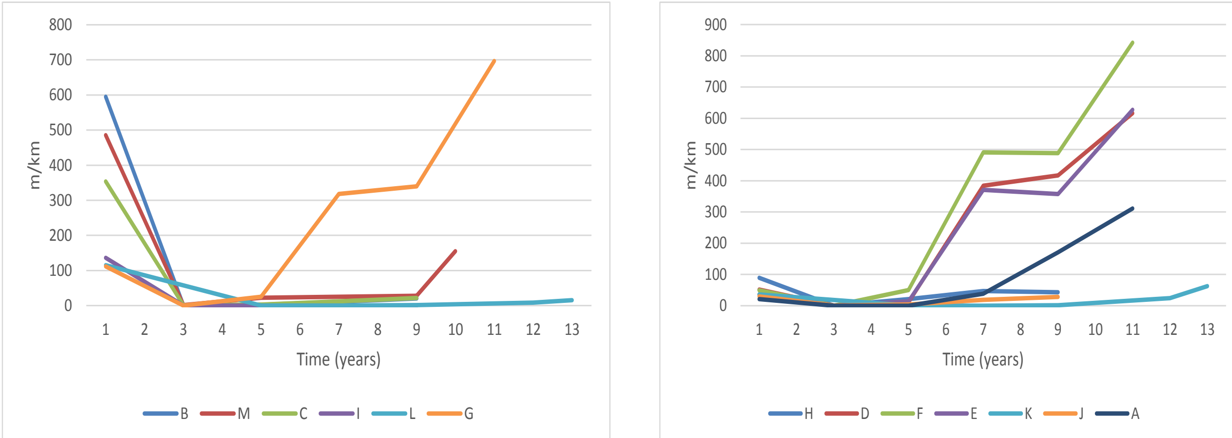


Figure E.11. Low longitudinal cracking on wheelpath

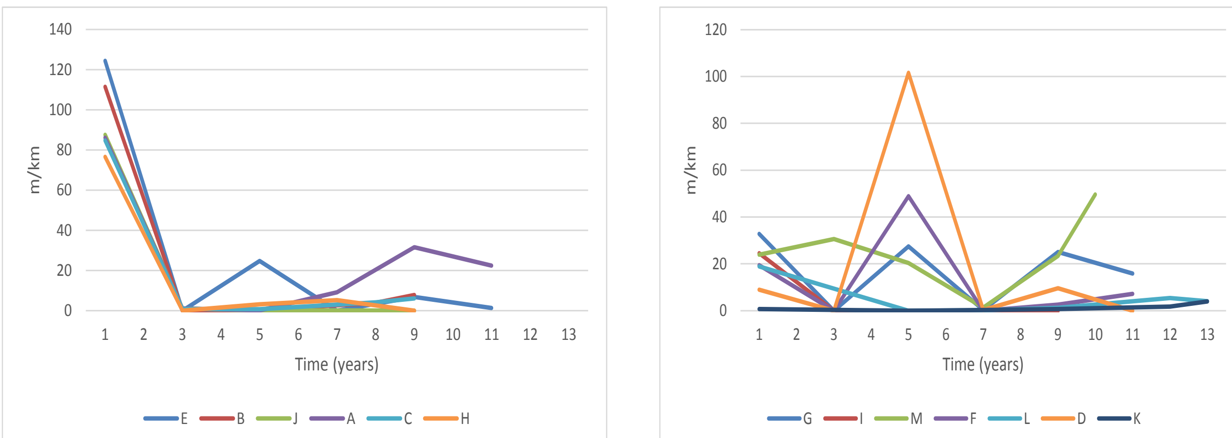


Figure E.12. Moderate longitudinal cracking on wheelpath

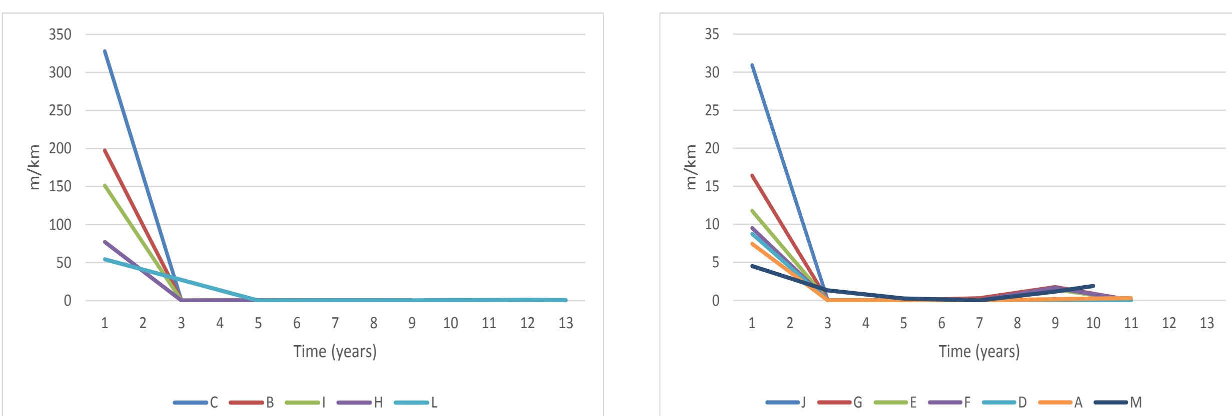


Figure E.13. High longitudinal cracking on wheelpath

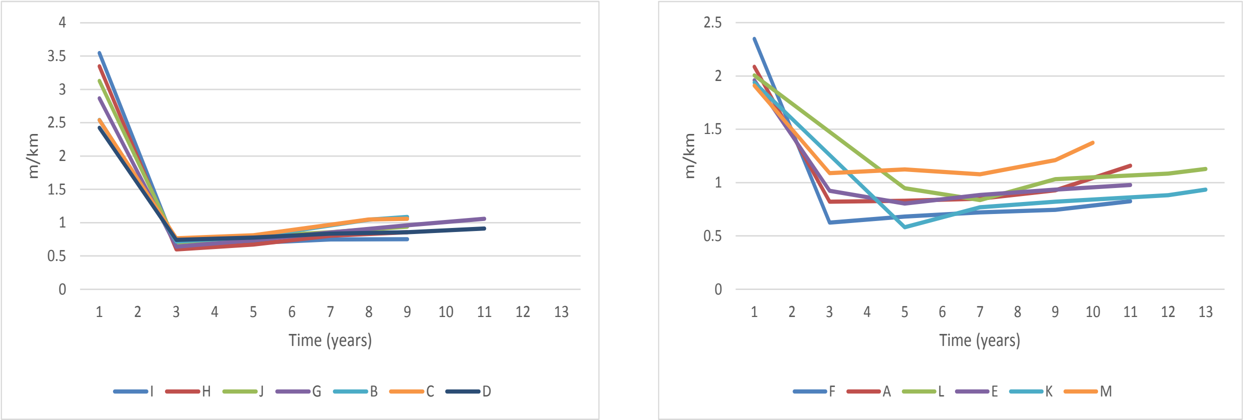


Figure E.14. IRI on left wheelpath

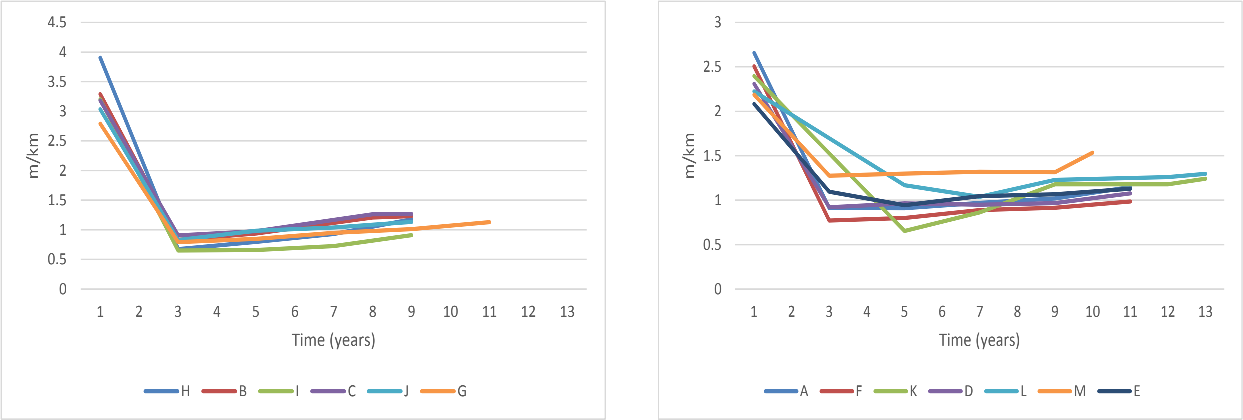


Figure E.15. IRI on right wheelpath