Asset Management and Safety: A Performance Perspective

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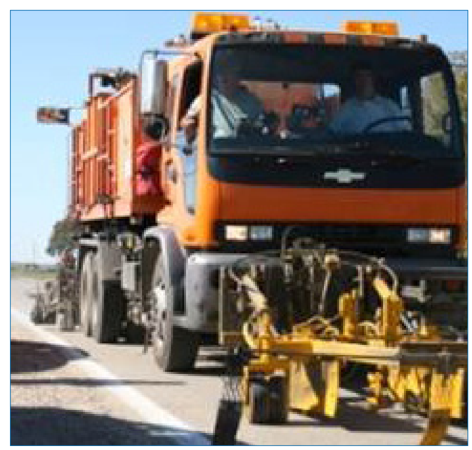
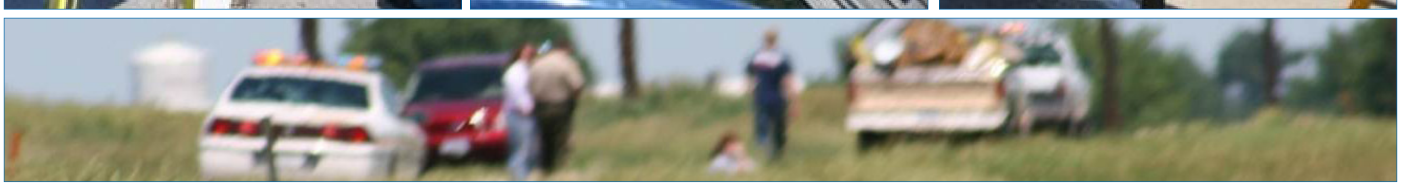
Center for Transportation Research and Education

Final Report
September 2012



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16. Abstract

Incorporating safety performance measures into asset management can assist transportation agencies in managing their aging assets efficiently and improve system-wide safety. Past research has revealed the relationship between individual asset performance and safety, but the relationship between combined measures of operational asset condition and safety performance has not been explored.

This project investigates the effect of pavement marking retroreflectivity and pavement condition on safety in a multi-objective manner. Data on one-mile segments for all Iowa primary roads from 2004 through 2009 were collected from the Iowa Department of Transportation and integrated using linear referencing.

An asset condition index (ACI) was estimated for the road segments by scoring and weighting individual components.

Statistical models were then developed to estimate the relationship between ACI and expected number of crashes, while accounting for exposure (average daily traffic).

Finally, the researchers evaluated alternative treatment strategies for pavements and pavement markings using benefit-cost ratio analysis, taking into account corresponding treatment costs and safety benefits in terms of crash reduction (number of crashes proportionate to crash severity).

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ASSET MANAGEMENT AND SAFETY: A PERFORMANCE PERSPECTIVE

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Principal Investigator
Omar Smadi, PhD
Director and Research Scientist
Roadway Infrastructure Management and Operations Systems, Iowa State University

Co-Principal Investigators
Neal R. Hawkins, PE
Director
Center for Transportation Research and Education, Iowa State University

Konstantina Gkritza, PhD
Assistant Professor of Civil, Construction, and Environmental Engineering
Center for Transportation Research and Education, Iowa State University

Postdoctoral Research Associate
Basak Aldemir Bektas, PhD
Center for Transportation Research and Education, Iowa State University

Graduate Research Assistant
Jian Gao

Authors
Jian Gao, Konstantina Gkritza, Omar Smadi, Neal R. Hawkins,
Basak Aldemir Bektas, Inya Nlenanya

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A report from
Center for Transportation Research and Education
Iowa State University
2711 South Loop Drive, Suite 4700
Ames, IA 50010-8664
Phone: 515-294-8103 Fax: 515-294-0467
www.intrans.iastate.edu

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The researchers would like to thank the Midwest Transportation Consortium for sponsoring this research. The researchers also want to acknowledge the Iowa Department of Transportation for providing data to support this project.

EXECUTIVE SUMMARY

Incorporating safety performance measures into asset management can assist transportation agencies in managing their aging assets efficiently and improve system-wide safety. Past research has revealed the relationship between individual asset performance and safety, but the relationship between combined measures of operational asset condition and safety performance has not been explored.

This project investigates the effect of pavement marking retroreflectivity and pavement condition on safety in a multi-objective manner. Data on one-mile segments for all Iowa primary roads from 2004 through 2009 were collected from the Iowa Department of Transportation and integrated using linear referencing.

An asset condition index (ACI) was estimated for the road segments by scoring and weighting individual components.

Statistical models were then developed to estimate the relationship between ACI and expected number of crashes, while accounting for exposure.

Finally, the researchers evaluated alternative treatment strategies for pavements and pavement markings using benefit-cost ratio analysis, taking into account corresponding treatment costs and safety benefits in terms of crash reduction (number of crashes proportionate to crash severity).

Key Findings

Estimation of Asset Condition Index

The ACI was developed as a simple, convenient, and easy-to-understand indicator for representing the overall physical asset condition of a roadway segment and assisting agencies in decision-making for pavement preservation and maintenance activities.

The researchers developed a step-by-step methodology for calculating the unique condition index using multiple asset condition measures. The methodology involved scaling and weighting asset condition components, such as pavement condition and pavement retroreflectivity, as well as their subcomponents. The resulting ACI values range from 1, indicating poor condition, to°3, indicating good condition.

Statistical Analysis

Negative binomial models were estimated to predict the relationship between crash frequency and ACI, while accounting for exposure. The estimation results indicated that the higher the ACI of a roadway segment, the lower the expected number of crashes.

In addition, the researchers found that separate negative binomial models for different ACI ranges explain the relationship among crash frequency, ACI, and exposure (average daily traffic or ADT) better than a single model. The impact of ACI on crash frequency for roadway segments with an ACI lower or equal to 1.5 was greater than that for roadway segments with an ACI higher than 1.5.

Economic Analysis

Both short-term and long-term safety benefits in terms of crash reduction along with treatment costs were estimated for six alternative treatment strategies via a single-year benefit-cost ratio (BCR) analysis and a five-year net present value (NPV) analysis.

Minor rehabilitation and use of durable pavement marking materials are recommended as more cost-effective treatment alternatives in the short-term. In the long-term, the same recommendation holds for segments with an ACI higher than 2.0. For segments with an ACI lower than 1.5, major rehabilitation and tape marking are recommended.

Study Limitations

The limitations pertaining to this study are discussed in the Conclusions and Recommendations.

Recommendations for Future Research

To understand the relationship between asset performance and safety performance better, the following recommendations are offered for future studies.

- *Analysis of future data:* A longer study period for the database developed in this study would help to define the relationship between asset performance and safety performance more accurately. A further process of relating crashes to asset performance measures, based on crash reasons, is expected to improve the accuracy of the research.
- *Replication of this study in other states:* A replication of this study in other states would help verify the results and/or identify differences among states. Similar data resources would be necessary.
- *Consideration of additional asset performance measures:* Only pavement condition and pavement marking performance were included in this study. Additional asset conditions that could be considered in future work include sign inventory, lighting inventory, rumble strip inventory, or guardrail locations.

1. INTRODUCTION

1.1 Problem Statement

Asset management (AM) is an efficient approach to manage the performance and investment in roadway infrastructure. AM concepts, principles, and performance measures have received increasing attention from transportation agencies and transportation leaders in the US and abroad in the last two decades.

AM concepts and tools utilize tradeoff analysis and multi-criteria decision making by incorporating system-wide costs and benefits of alternative strategies.

The Iowa Department of Transportation (DOT) has a rich history in the implementation of infrastructure management systems, such as pavement, bridge, and pavement marking management systems, and, consequently, has comprehensive historic data for different assets.

Recently, the Iowa DOT started its own asset management implementation process. This decision was made, not only because of the economic recession, but also due to the desire for a systematic, efficient, and critical methodology for fiscal investment.

In addition, as a state with a low crash rate and one of the best safety databases in the country, the Iowa DOT is interested in assessing safety benefits or the effect on safety of any project or management system.

In 2011, the total fatalities on Iowa roadways were 364, which is the lowest number of deaths since 1944, and the crash rate has dropped to less than one fatality for every 10,000 registered vehicles (Iowa DOT 2012), which is lower than the nationwide average (about 1.2 fatalities per 10,000 registered vehicles in 2009) (NHTSA 2009).

While past research has revealed the relationship between individual asset performance (such as pavement condition and pavement marking retroreflectivity) and safety, the relationship between combined measures of operational asset condition and safety performance has not been fully examined.

Furthermore, to date, the impact of alternative strategies on safety has not been included in the decision-making framework. Therefore, a need exists to develop a methodology for investigating the relationship between asset performance and safety and further investigate the feasibility of developing a methodology to prioritize safety improvements based on this relationship.

Incorporating safety performance measures into asset management can assist agencies in managing their aging assets efficiently and improve safety, system-wide.

1.2 Research Objectives and Tasks

The objectives of this study were as follows:

- Develop a methodology for estimating an index that represents overall physical asset condition on a roadway segment
- Investigate the effect of asset condition on safety and develop a methodology to prioritize safety improvements based on asset condition

To achieve these objectives, the following tasks were conducted.

Task 1: Review of Literature

The literature review included the overview of asset management, the potential benefits of integrating safety into asset management, and the review of selected asset performance and safety measures.

Task 2: Descriptive Data Analysis

The datasets from different management systems, such as the Iowa DOT Pavement Management Information System (PMIS) and Iowa Pavement Marking Management System (IPMMS) are introduced, summarized, and interpreted using descriptive analysis techniques and geographic information systems (GIS). The Iowa DOT crash datasets were also used in this study.

Task 3: Integration of different data sets

The collected datasets were integrated using the Iowa DOT linear referencing system (LRS).

Task 4: Estimation of Asset Condition Index

An ACI was developed as a simple, convenient, and understandable indicator for representing the overall physical asset condition of a roadway segment. The step-by-step methodology for calculating a unique condition index of multiple asset conditions can assist agencies in monitoring asset condition using a convenient indicator.

Task 5: Investigation of Relationship between Asset Performance and Safety Performance

The relationship between crash frequency and ACI was investigated, taking into account traffic exposure (average daily traffic or ADT). Statistical analyses were conducted to select appropriate models to estimate the relationship between ACI, exposure, and number of crashes. Separate models were developed for ACI ranges as explained later in this report.

Task 6: Evaluation of Different Asset Treatment Strategies

A single-year benefit-cost ratio (BCR) analysis and five-year net present value (NPV) analysis were conducted. Both short-term and long-term safety benefits and treatment costs were estimated for six alternative treatment strategies. Recommendations based on the analysis are presented as well.

Task 7: Conclusions and Recommendations

Based on the work conducted in the previous tasks, some concluding remarks and recommendations are offered. Additional research needs for future studies were also identified.

2. LITERATURE REVIEW

2.1 Asset Management

2.1.1 Definition of Asset Management

AM is a systematic process of maintaining, upgrading, and operating physical assets cost-effectively (Office of Asset Management 1999). AM combines engineering principles with business practice and economic rationale for resource allocation and utilization with the goal of better decision-making based on quality information and well-defined objectives. (OECD 2001).

The Asset Management Primer from the Federal Highway Administration (FHWA) indicates that AM is a decision-making framework, which is guided by goals of performance (Office of Asset Management 1999). AM should help highway agencies develop improvement plans and budget allocation policies to maintain, repair, or replace infrastructure cost-effectively and at the appropriate time (Haas 2001).

AM also encompasses principles of engineering, engineering policies, economics and business management, and provides tools for both short-term and long-term planning and decision-making. Business practices from both the public and private sectors are taken into account in an AM system (Falls, et al. 2001).

According to the FHWA, an AM system should include 13 components, as follows (Office of Asset Management 1999):

- Strategic goals
- Inventory of assets
- Valuation of assets
- Quantitative condition and performance measures
- Measures of how well strategic goals are being met
- Usage information
- Performance-prediction capabilities
- Relational databases to integrate individual management systems
- Consideration of qualitative issues
- Links to the budget process
- Engineering and economic analysis tools
- Useful outputs, effectively presented
- Continuous feedback procedures

These components could be grouped into five major functions (Krugler, et al. 2006):

- Basic information
- Performance measures

- Needs analysis
- Program analysis
- Program delivery

Figure 2.1 shows the comprehensive relationship between the five functions and the 13 basic components of AM.

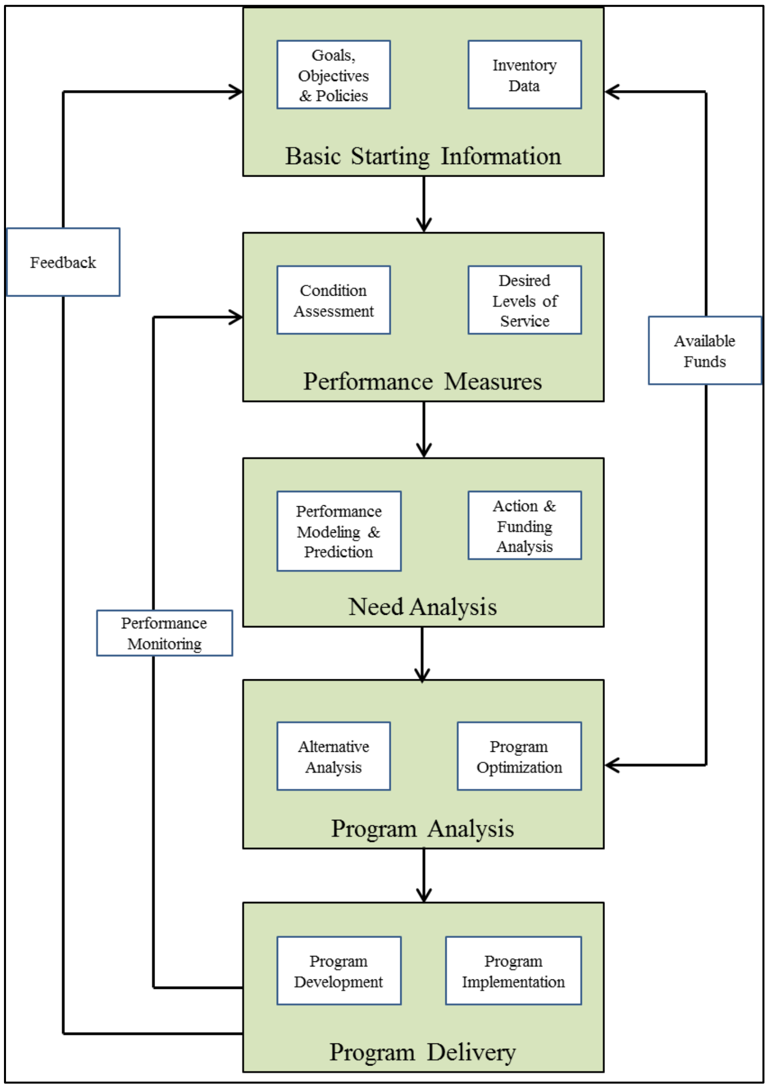


Figure 2.1. Components of an asset management system (Smith 2005)

This is a simplified and recommended flow of the system that agencies can modify depending on their own data history and availability, resources, desired level of service, and so forth.

In 2002, the Transportation Association of Canada presented an overall framework of AM as shown in Figure 2.2.

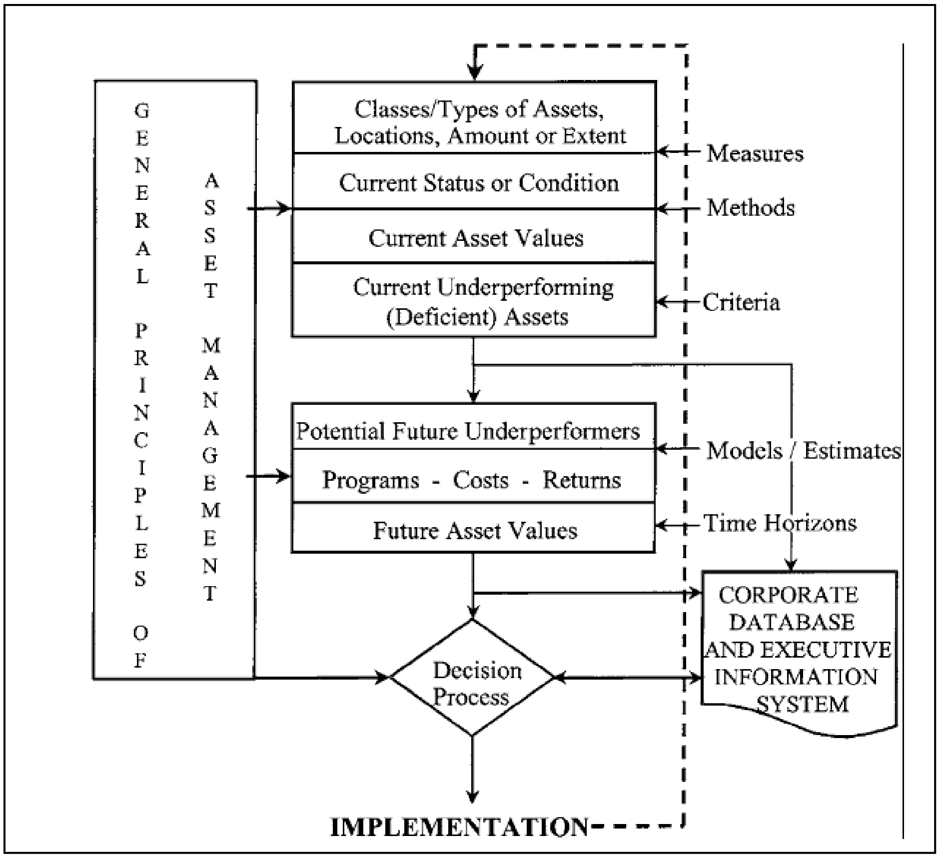


Figure 2.2. Overall framework for asset management (Falls, et al. 2001)

To offer an effective process guide to transportation agencies for implementing AM, the American Association of State Highway and Transportation Officials (AASHTO) also developed and adopted the Guide for Transportation Asset Management in 2002. In this guide, the principles of policy goals, objectives, and performance measures are also presented in a generic framework.

These frameworks have been provided to DOTs and other transportation agencies to guide AM implementation.

AM is still in its infancy although the concept originated almost 20 years ago (Winsor, et al. 2004). Agencies are still exploring both state-of-the-art and state-of-the-practice theories to improve their AM system by sharing and communicating best practices. The Transportation Asset Management Today (TAMT) website was established in 2000 as a national platform to contribute to the communication between agencies, practitioners, and academia within the US. Together, with the FHWA Asset Management website, the two websites serve as communication networks for AM at the national level.

2.1.2 AM and Pavement Management

For many years, state DOTs have viewed AM as two separate systems: pavement management and bridge management (Krugler, et al. 2006). While the general AM framework is similar to the network-level programming of a pavement management system (Haas and Chairman, 2001), individual AM systems in no way replace AM (Office of Asset Management 1999). AM applies to all infrastructure assets beyond pavements and bridges.

Pavement management systems were the first systems implemented to manage assets, so agencies have the most experience with them. This experience can guide agencies in implementing AM principles to other infrastructure assets. Bridge management systems are common AM systems but with a relatively shorter history.

2.1.3 Potential Benefits of Integrating Safety Elements in AM

The primary benefits of AM implementation are savings in human lives, as well as resources, which are very important considerations for all road agencies. More specific benefits are summarized as follows (FHWA 2005):

- *Better resource allocation decisions.* AM techniques and tools help agencies to optimize the resource expenditure plans for asset maintenance, upgrades, and operations rationally. The rationale for expenditure decisions can be provided easily to upper management, other decision makers, the public, and the media.
- *Simplified economic processes and cost saving.* AM tracks costs. This cost tracking could support the preparation of more detailed and accurate cost estimates and budget plans. In addition, with better information, more accurate cost data, more timely decisions, and other efficiency improvement plans, agencies could reduce the costs of maintenance, upgrade, and operating of assets.
- *Improving data access.* AM requires creating a complete, timely, and accurate database that can be accessed quickly. The inventory of assets, their location, condition, maintenance and repair history, and other relevant information can be shared in real time and updated continually. Easy access to information helps managers, executives, policymakers, and other relevant officers of an agency to make better decisions.
- *Improved data clarity and consistency.* The consistency of the shared standard definitions, measurements, and formats improve the accuracy and reliability of data.
- *Improved safety through faster response to customer service requests.* Consideration of the safety of signs, lightings, pavement markings, and other roadway safety elements account for a significant part of the interaction between transportation agencies and users. Quicker access to data about the safety elements facilitates faster customer service and makes roads safer.
- *Reduced duplication effort*. Because central and regional offices can share information, duplication of effort (for example, multiple data entry) is reduced or eliminated.

2.2 Review of Select Asset Performance and Safety Measures

The literature review revealed that very limited research has focused on the relationship between asset physical performance and safety performance. However, previous studies have been conducted for selected elements, such as pavement condition, pavement marking retroreflectivity, sign condition, and lighting, and their relationships to safety. Based on the previous findings, each element has a different effect on safety.

The following research sections describe the existing literature on the relationship between asset condition and safety.

2.2.1 Pavement Condition

Among studies, pavement condition was found to have significant effect on highway safety, and the magnitude of the effect could vary depending on the selected pavement condition measure and the confidence level of the analysis.

Few statewide studies on pavement distress and safety existed before 1990 because the data collection methodologies were not developed well enough before then. Studies conducted in recent years can be divided, basically, into experimental studies and simulation studies. However, research studies about safety and pavement distress are still few, and most of them focus on a single type of distress, such as rutting or roughness, as it relates to safety (Chan, et al. 2008).

The severity of crashes related to pavement edge drop-off depends on several factors, such as speed, shoulder geometry, and lane width (Ivey, et al. 1990). Start et al. 1998 found that pavement rutting of 0.3 in. or deeper would significantly increase crash rate (Start, Kim and Berg 1998).

Pavement roughness can also be measured by the International Roughness Index (IRI) or Riding Number (RN) (Chan, et al. 2008). IRI has become the standard for assessing pavement surface roughness in recent years. IRI is based on a quarter-car model traveling the pavement surface at a constant speed.

IRI has been proven to explain phenomena such as pavement performance and pavement deterioration satisfactorily (Surface Properties–Vehicle Interaction Committee 2009). The transportation department of New Zealand conducted a study on crashes from 1997 to 2002. The results indicated that crash rate does not have a significant relationship with both IRI and rutting depth (Cenek and Davies 2002).

Conversely, previous work has shown that the higher the IRI, the lower the brake force (Nakatsuji, et al. 1990), the higher the difference of friction on each tire (Chan, et al. 2008), and the higher the probability of crashes (Burns 1981).

In addition, the relationship between the Present Serviceability Index (PSI) and crash rates on rural roads was found to have a significant effect on single- and multiple-vehicle crash rates, but no statistical influence on the total crash rate (Al-Masaeid 1997). PSI has been indicated as the second most important safety factor for rural two-lane highways and the fifth most important factor for rural multilane highways (Karlaftis and Golias 2002).

A study in Victoria, Australia examined the relationship between road surface characteristics, such as macrotexture, rutting, and roughness, and safety (Cairney and Bennett 2008). The study found that the higher the macrotexture of the pavement, or the better the condition, the lower the crash rate. Furthermore, the study showed that crash rate decreases, following an exponential distribution, when macrotexture increases.

This study also found that the relationship between rutting and crash rate could be expressed by a power function, although with a relatively low confidence factor, which could suggest that the depth of the rutting might not have a significant or direct effect on the crash rate. On the other hand, the relationship between roughness and crash rate was found to follow a power function almost exactly, and the authors concluded that roughness significantly affects crash rates.

In terms of classification, for joint faulting, the Washington State DOT (WSDOT) set the limitation as 2.5 mm and 4 mm as acceptable and maintenance required thresholds, respectively (Pavement Interactive 2011), and NCHRP Synthesis 334 suggests pavement faulting depth of 2.5 mm as acceptable and 5.0 mm or higher as a poor level (McGhee 2004).

For rutting depth, 6 mm and 15 mm are common criterion for good and poor condition thresholds among agencies, such as the California DOT (Caltrans) and MaineDOT (Gallivan 2003) (MaineDOT 2006).

In terms of friction, the NCHRP Guide for Pavement Friction indicated that road segments with a friction number (FN) of 60 would be considered as good (Hall, et al. 2009), while the NCHRP Synthesis 291 report suggested that FN lower than 35 should be considered as poor and maintenance could be performed (Henry 2000).

2.2.2 Pavement Marking Retroreflectivity

The review of the limited studies on the effect of pavement marking retroreflectivity on safety revealed mixed findings. A National Cooperative Highway Research Program (NCHRP) study conducted by iTRANS Consulting of Ontario, Canada found no significant effect of pavement marking and marker retroreflectivity on crash rate (Harrigan 2006). More specifically, the presence and visibility of markings are important to drivers, but whether the markings have high retroreflectivity or relatively low retroreflectivity is less important with respect to safety.

One hypothesis is that drivers compensate by reducing their speed under lower visibility conditions, and maintain higher speeds under higher visibility (Bahar, et al. 2006). However, Smadi et al. (2008) conducted a three-year statistical analysis of pavement marking retroreflectivity data and crash rates that were collected by the Iowa DOT on all Iowa primary roads and the study indicated that the higher the retroreflectivity of pavement markings, the lower the relative crash probability, regardless of traffic volume. This result applied to both yellow and white edge lines on either freeways or two-lane roads (Smadi, et al. 2008).

The minimum levels of marking retroreflectivity have been studied as well. The 3M Company conducted a study where subjects drove a test road marked similarly to one side of a four-lane freeway in 1986. A minimum retroreflective value of 100 mcd/m^2/lux was suggested as a conservative recommendation due to instrument variability (Ethen and Woltman 1986).

The Minnesota DOT (MnDOT) sponsored a 1998 study that used a sample of drivers in the state to assess minimum pavement marking retroreflectivity. The study found that 90 percent of the participants rated yellow markings with a retroreflectivity of 100 mcd/m^2/lux as acceptable. In addition, the researchers found that the acceptability ratings of the pavement markings increased dramatically as the retroreflectivity increased from 0 to 120 mcd/m^2/lux, much less as the retroreflectivity increased from 120 to 200 mcd/m2/lux, and almost none as the retroreflectivity increased beyond 200 mcd/m2/lux. The researchers recommended that MnDOT use 120 mcd/m^2/lux as the threshold between acceptable and unacceptable pavement marking retroreflectivity in its pavement marking maintenance program (Loetterle, et al. 2000).

The NCHRP Synthesis 306 report states that minimum retroreflectivity of yellow marking is 100 mcd/m^2/lux and 150 mcd/m^2/lux for white marking. Also, any pavement marking retroreflectivity beyond 200 mcd/m^2/lux should be considered as in good level (Miglets and Graham 2002).

3. DATA DESCRIPTION

The data sources that were used in this project include Iowa DOT crash data, pavement condition data, pavement marking retroreflectivity data, and other inventory data from their Geographic Information Management System (GIMS) database.

The following sections describe each data source in detail.

3.1 Crash Data

The Iowa DOT collects information on crashes that occur on all Iowa public roads. However, crashes that result in less than $1,500 in property damage only (PDO) are not required to be reported in Iowa.

This study used crash data for Iowa primary roads from 2004 through 2009. These data include crash location, date and time, coordinate information, and crash severity. Table 3.1 provides descriptive statistics of the crashes and Figure 3.1 shows the distribution of crashes per mile year by plotting the mean values over the six-year period.

Table 3.1. Descriptive statistics (variable: crashes per mile)

	Mean	Std. Dev.	Observations (#)
All	2.1325	6.3224	54,798
2004	0.7486	2.6797	9,912
2005	2.2572	6.8589	9,939
2006	2.0875	6.2201	9,902
2007	4.3141	8.7265	5,316
2008	2.2130	6.6004	9,803
2009	2.1865	6.2869	9,926

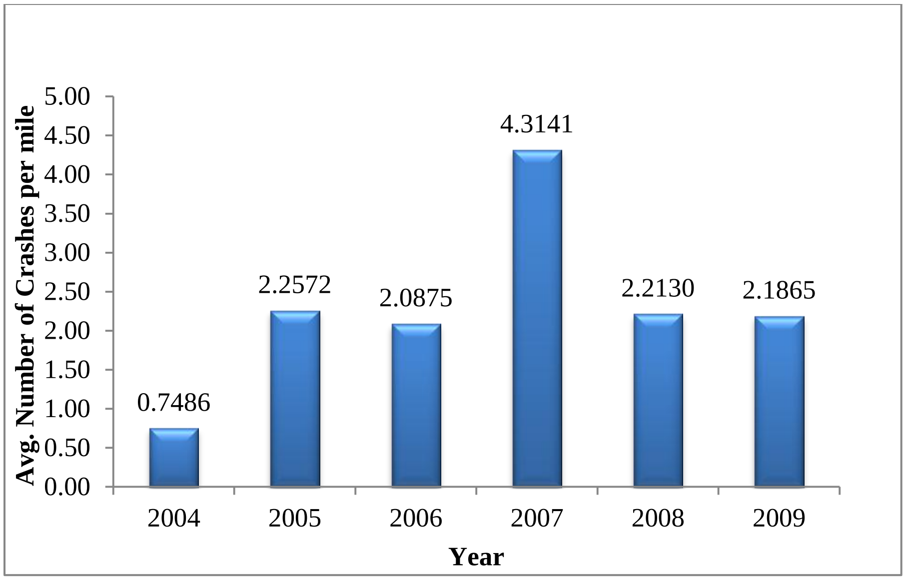


Figure 3.1. Distribution of crashes per mile

3.2 Pavement Condition Data

The pavement condition data were available from the Iowa DOT PMIS for state primary roads from 2004 through 2009. In each year's data file, information such as year and date when the pavement condition was measured, segment number, road classification, route, direction, segment beginning/end mile post, length, construction year, PCI, international roughness index (IRI), faulting depth, rut depth, friction number, and ADT are available.

An example of a plotted map is shown in Figure 3.2. The figure shows the statewide PCI distribution. PCI values from 0 to 33 indicate poor pavement condition, 34 to 67 indicate fair pavement condition, and 68 to 100 indicate good pavement condition.

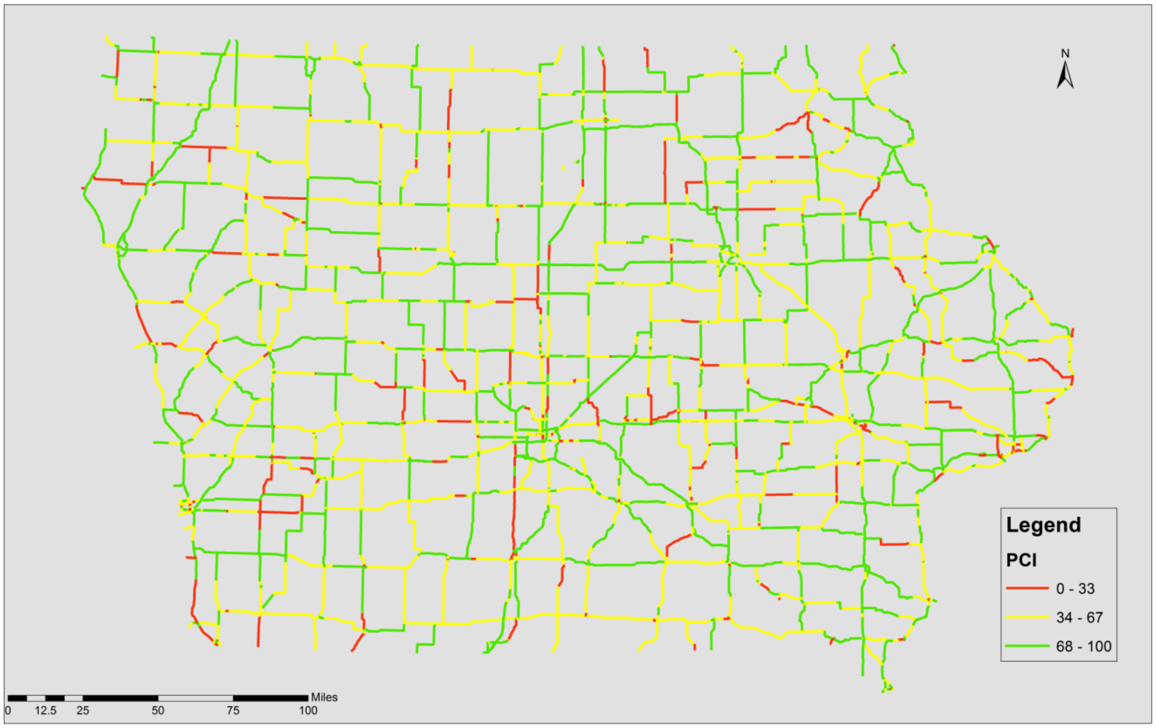


Figure 3.2. Sample Iowa primary roads pavement condition data map

3.3 Pavement Marking Retroreflectivity Data

Pavement marking retroreflectivity data were available from 2004 through 2010 using the IPMMS. The Iowa DOT collects pavement marking retroreflectivity on state primary roads twice each year, in the fall and spring.

The data fields include route information, milepost, line type, direction, retroreflectivity value, date when the measurements were taken, material type, marking length (five-mile segmentation), and coordinate information.

In addition to the seasonal databases, the repainting database was also available and used. Every year, the Iowa DOT re-strips low retroreflectivity markings from April to September, so separate databases indicating repainted markings information were generated. The availability for this repainting database was 2004 through 2008, including painting dates, length, beginning/end mileposts, directions, retroreflectivity value, and other related information.

Pavement marking retroreflectivity maps by season for each year were generated using GIS. Figure 3.3 shows an example of one of these maps. A higher value indicates better pavement marking retroreflectivity.

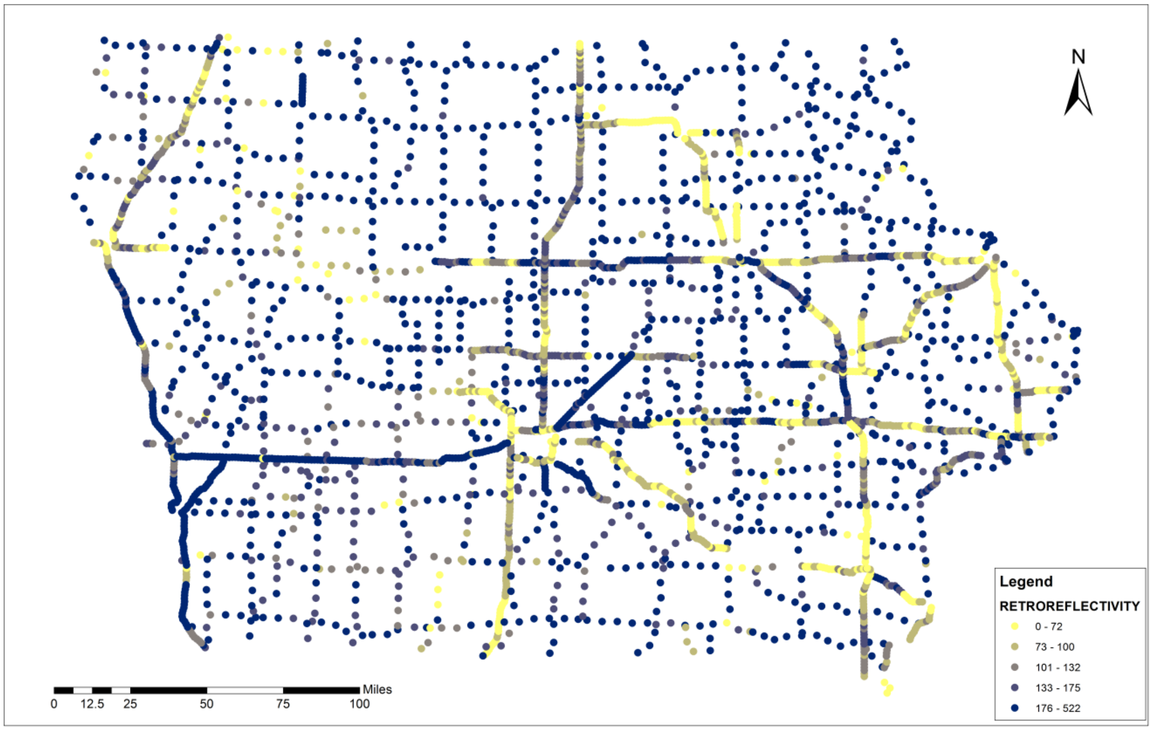


Figure 3.3. Sample Iowa primary roads pavement marking retroreflectivity data map

3.4 Linear Referencing System (LRS)

Iowa DOT GIMS data, such as latitude and longitude, route, milepost, direction, and so forth, were collected including information on all Iowa primary roads by route and mileposts in 2010. The LRS integrates disparate roadway data using the linear locations as a common link.

This GIMS file was used for data integration by the location reference, instead of the GIS. Fixed segmentation was utilized by the location reference-based integration, and results were compared between the two methods.

4. DATA INTEGRATION

As one of the most important processes under asset management, data integration provides spatial relationships between agency assets, enabling agencies to prioritize maintenance needs as well as evaluate returns on asset improvements.

Two data integration methodologies were undertaken for this study: pure GIS-based integration and route milepost-based integration. The GIS-based method used the spatial integration and joining method, while the route milepost-based method applied the location-referencing method (LRM) to integrate assets by highway location and segments.

4.1 Data Integration Concepts in Asset Management

4.1.1 Data Integration and AM

Data integration is defined as the "process of combining or linking two or more data sets from different sources to facilitate data sharing, promote effective data gathering and analysis, and support overall information management activities in an organization" (FHWA, Data Integration Primer 2010).

System-level transportation decision-making, which is a primary goal of AM, requires different levels of asset data as inputs. With these inputs, data integration provides the spatial relationship between assets. In addition, data integration supports comprehensive decision-making processes, with quick and convenient access to data, as well as further economic analysis.

The data integration process includes the following: 1) requirement analysis, 2) data and process modeling, 3) alternatives, definition, evaluation, and selection, 4) database design and specification, and 5) development, testing, and implementation (FHWA 2010).

Requirement analysis consists of business processes, such as handling data problems; user requirements, such as purpose and uses of data; character of agency and its skills and staff capabilities; data characteristics, such as data collection method and data type; and information system infrastructure, such as hardware or software requirements.

After analyzing data requirements, process modeling represents the datasets and their relationships graphically. In addition, process modeling may estimate a flow diagram, helping to determine the design specification.

With the design flow diagram or dataset relationships, alternatives of database type should be listed, evaluated, and selected. Common database types include fused database (single server) and interoperable database (numerous databases with computer network links).

Once the database type is determined, the next step is database design. This process is comprised of data model selection (structure and configuration of the database), data standards identification, data reference system selection, metadata and dictionary estimation, computer communication, etc. (FHWA, Data Integration Primer 2010).

The database design phase is followed by prototype development, testing or evaluation of the data models or interface, and, finally, implementation of the integrated data.

4.1.2 Common Methods of Integrating

Currently, the most commonly used data integration tools or techniques include dynamic segmentation, geo-coding/LRS, and structured query language (SQL) relationships. Geo-coding and SQL are commonly-used tools for data integration.

Dynamic segmentation is the process of computing the spatial locations or segments of events for highway assets stored and managed in an attribute table using a linear referencing measurement system. Dynamic segmentation allows integration of multiple data events, data queries, and event analysis among databases and provides visualization of datasets linked to a common LRS. Past work has argued that dynamic segmentation is the most powerful and suitable way for integration of AM databases (Ogle, Alluri and Sarasua 2011).

Applied to AM, GIS not only facilitates data collection, processing, and display, but also integrates asset mapping with project management and budgeting tools so that construction, operational, and maintenance expenses can be managed and accounted for centrally. Once established, AM systems provide a framework to allocate scarce resources efficiently and equitably among competing objectives.

Field personnel can take detailed GIS information with them on any number of mobile devices, locate relevant facilities quickly, and perform detailed inspections. Deficiencies identified during inspection can generate new work orders for maintenance and repair (ESRI 2010).

Two applications of GIS for data integration related to AM systems are as follows:

- The University of Northern Iowa investigated heuristic or experience-based artificial intelligence (AI) methodologies to optimize snow removal for winter road and bridge maintenance in Iowa. (Salim, Strauss and Emch 2002). An Iowa DOT GIS database, which included traffic volume and roadway inventory information for all roads in the case study area (Black Hawk County, Iowa), was obtained and integrated with the knowledge-based expert snow removal management system created by the researchers.

- GIS was used in Pierce County, Washington to integrate information and build an AM system on 190 traffic signals, more than 1,000 street lights, 33,420 traffic signs, and about 1,500 miles of road in the county (Butner and Lang 2009).

4.2 Route Milepost-Based Integration

As a second method of data integration, a fixed segmentation road reference was used and integrated so each row of the final data would represent a one-mile road segment, instead of a crash, and models of crash number and asset condition could then be estimated for each road segment by milepost. The following procedures were applied for each year from 2004 through 2009 and consolidated for all years.

4.2.1 Processes

Step 1: Road Reference Preparation

The first step was to extract data needed from REFERENCE_POST_2010 in the LRS dataset. The route milepost reference that was prepared consisted of 11,955 rows, and each row represents a milepost segment on different primary routes with a default direction of Dir.1 (North or East). If the segment is divided by median, two rows presenting the same route and milepost occurs, with Dir. 1=North/East and Dir. 2=South/West.

Step 2: Pavement Condition Data Integration

Pavement condition data were integrated by dynamic segmentation with each observation indicating pavement condition values for various lengths of segments, with the lengths represented by beginning and ending milepost.

Considering this situation, the pavement condition data were joined directly using Microsoft Access with the designed query as a homogeneous route and direction in both datasets and referenced mileposts as smaller or greater than ending or beginning pavement condition data milepost, respectively.

Step 3: Pavement Marking Dataset Consolidation

Both the seasonal detected data and the repainting retroreflectivity data are available in spreadsheet format, and both datasets are connected by the project so that a more comprehensive asset condition dataset could be compiled.

While consolidating the data, the researchers noticed that the milepost information in the repainting dataset coincides with the pavement condition data, in that, beginning and ending milepost information are present for each repainted segment.

On the other hand, the seasonal retroreflectivity data used a fixed segmentation of five miles. As a result, a similar procedure was undertaken to integrate marking retroreflectivity datasets, with an additional query of join by the same line type (with WEL for white edge line, YEL for yellow edge line, YCL for yellow centerline, and WDL for white dash line).

Step 4: Pavement Marking Retroreflectivity Data Integration

Given the pavement marking data were collected with a five-mile segmentation, the dataset was enriched based on the assumption that each individual data value represents the retroreflectivity value within the nearest five miles (data located +2 mileposts forward and +2 mileposts backward). This modified dataset was then integrated with the extracted data in a manner consistent with the other Access queries for this project.

Step 5: Sign Data Integration

The sign inventory includes two parts: sign location and sign detail. Before integrating, the two parts were combined by the unique ID of each data row. Route and milepost information were already included, and the integration by route milepost was accomplished directly.

Given this project focus is on the safety effect of the number of signs and sign condition, regardless of sign direction, the sign facing direction was not considered as a criteria in integrating these data.

Step 6: Crash Data Preparation and Integration

The original crash data from the Iowa DOT do not have milepost information available. As a result, it was required to prepare and modify the crash data before integrating them with other datasets.

The crash data were spatially joined with the GIMS map, again, and another GIMS file, GIMS_MP_2010, was used.

In addition, the offset criteria of 30 meters for rural areas only and route number preparation was conducted as before so the error could be minimized. After integrating by the same manner as previous steps, about 140,000 rows were included in the final integrated data. However, the data include many duplicate rows with the same information, except for crash ID, and this is because each row is representing a comprehensive information row for a single crash.

A pivot table summary indicating pavement condition, marking retroreflectivity, and crash number, was created and, at this point, the final integrated dataset was ready for further modification and study.

4.2.2 Data Modification—Pavement Retroreflectivity Data Gaps Sufficiency

In the IPMMS dataset, pavement marking retroreflectivity was measured with five-mile segmentation. Compared to other datasets, such as the pavement condition dataset, which has a dynamic segmentation with the segment lengths within the rage of 0.5 to 1.5 miles, the pavement marking retroreflectivity dataset has a relatively long segmentation.

In this case, with the data integration result produced by milepost, every five miles has a single retroreflectivity data value. This situation could result in a potential inaccuracy or error for the study. Thus, an assumption was made that every retroreflectivity reading represents an average marking retroreflectivity within the nearest five miles, with 2.5 miles in front of the segment and 2.5 miles further from the segment for the same route index and direction.

With the assumption, a pavement retroreflectivity data gap sufficiency procedure was developed, and the result of the fulfilled dataset was expected to produce more accurate results and better-developed relationship estimation between asset condition and safety performance.

4.3 Summary

In the field of transportation engineering, large amounts of data are generated from management systems, such as an AM system. Datasets come in different formats, resulting in the need for innovative techniques in terms of managing, editing, plotting, integrating, and analyzing these data.

In this study, datasets were integrated focusing on both crashes and roadway segments and results indicated that the route milepost-based integration is a more applicable method, considering the integrated data characteristics.

5. ESTIMATION OF ASSET CONDITION

This chapter discusses the estimation the overall asset condition of a roadway segment using a unique index, the ACI. The ACI combines performance measurement data on pavement condition and pavement marking retroreflectivity, such as IRI, faulting depth, friction, rutting depth, white marking line retroreflectivity, and yellow marking line retroreflectivity. The ACI provides a numerical rating for the condition of road segments, where 1 is poor condition, 2 is moderate, and 3 is good.

5.1 Literature Review

Constructing an index to indicate condition given measures or performance is a widely used method in the field of transportation engineering and, in general, civil engineering. For instance, the U.S. Army Corps of Engineers (USACE) developed the PCI to represent the condition of a pavement surface as a numerical index between 0 and 100.

Another study provided a step-by-step methodology to construct a US transportation infrastructure index to help understand economic trends and promote prosperity throughout the business sector (Oswald, et al. 2011). This transportation index provides a rich source of historical information related to the performance of the complex and extensive transportation infrastructure system.

5.1.1 Weighting Methods

In multi-criteria decision-making, one of the key procedures is the explicit or implicit assignment of relative weights to each performance measure to reflect its importance among different criteria. Weighting was an important step in developing the ACI. To determine the most suitable methodology for weighting of the data, some typical weighting methods were reviewed, as summarized in Table 5.1.

Table 5.1. Summary of weighting methods

Method	**Description**
Equal Weighting (Sinha and Labi 2006)	Same weight assigned to all performance criteria Pros: Simple and easy Cons: May yield flawed results since it does not incorporate with the relative references that may exist among criteria Main procedure: Assume a weight of 1 for every performance measure

Method	Description
Direct Weighting (Li and Sinha 2009) (Sinha and Labi 2006)	Decision makers directly assign numerical weight values Two approaches: Easy but may not represent importance effectively • Point allocation: Assign weights by a number of points in proportion to their importance. Can be either global (assign specific weights to data ranges directly) or local (assign weight to one range first, and weight the rest relative to the assigned range) Pros: Cardinal rather than ordinal scale of importance (better meaning to relative importance of criteria/ measures) • Ranking-decision maker manually weights performance criteria/measures orderly, by decreasing importance as perceived Pros: Useful for large number of criteria/measures
Observer-Based Weighting (Sinha and Labi 2006) (Li and Sinha 2009)	Observer assigns scores to performance criteria or measures and their overall impact score; then, establishes a functional relationship between total scores (response variable) and individual scores assigned (explanatory variable) through regression analysis
Gambling Method (Sinha and Labi 2006) (Li and Sinha 2009)	1. Initial ranking of performance 2. Compare between two performance measures a. Sure thing: the measure is at its most desirable level (best performance) and the other is at the worst performance b. Gamble: in an outcome, set p (%) possibility that all criteria are at best level, and 1-p at the worst level 3. Repeat step 2 to derive the weights for remaining performance measures Pros: Useful for determining the relative weights of performance criteria in the outcome risk scenario Cons: May be difficult to comprehend or administer
Swing Method (Sinha and Labi 2006) (Li and Sinha 2009)	1. Hypothetically assign all criteria/measures at worst level 2. Determine the more preferred measure to swing from worst up to best 3. Determine the second preferred, and so on 4. The most preferred measure is assigned as a weight of 100, and second as a lower value, etc.
Indifference Trade-Off Weighting (Li and Sinha 2009)	Used for survey respondents

Method	Description
Pairwise Comparison of the Performance Criteria (Analytic Hierarchy Process/AHP) (Sinha and Labi 2006) (Li and Sinha 2009)	1. Decomposition: construct a hierarchy of levels 2. Comparative judgments: decision makers determine relative weights 3. Syntheses-relative weights are combined to establish the overall optimal weights 4. Check for consistency
Delphi Technique (Li and Sinha 2009)	Used for surveys to aggregate the perspectives from individual experts for consensus-building and ultimately for a holistic final assessment
Factor Analysis (Hermans, Van den Bossche and Geert 2008)	1. Following guidelines, assess the optimal factor number (Sharma, 1996) 2. Enhance the interpretability; results in each indicator having a large factor score on one of the factors only 3. Deduce indicator weights Pros: Reduce number of dimensions Cons: Weights are based on correlations that do not necessarily correspond to the real-world links between the phenomena being measured
Data Environment Analysis (DEA) (Hermans, Van den Bossche and Geert 2008)	Used for evaluating the relative efficiency of decision-making units (DMUs) with efficiency defined as the ratio of the weighted sum of outputs to the weighted sum of inputs A general DEA model for indices has been proposed in Cherchye et al. (2006) Most valuable when only one expert opinion is available Constraints: smaller than 1; non-negative Pros: Can handle raw values; weights are endogenously determined and derived directly from the data Cons: Implies that the weights do not sum up to one, which makes the comparison of indicator weights with other weighting methods impractical
Simple Multi-Attribute Rating Technique (SMART) (Poyhonen and Hamalainen 2001)	1. Rank the importance of the changes in the attributes from the worst to the best level 2. Make ratio estimates of the relative importance of each attribute relative to the one ranked lowest in importance

5.2 ACI Estimation

Pavement condition (PC) and pavement marking (PM) retroreflectivity are the two main components of the ACI. The sub-indices under PC are IRI, faulting depth, friction number, and rutting depth; and, the sub-indices under PM retroreflectivity are white marking line retroreflectivity and yellow marking line retroreflectivity.

The white marking line retroreflectivity is the average of retroreflectivity of the white edge line (WEL) and white dash line (WDL) in the road segment. Both of these line types are applied for dividing traffic in the same direction. On the other hand, the yellow marking line retroreflectivity sub-index includes the yellow edge line (YEL) and yellow centerline (YCL) on undivided roadways and divided roadways, respectively. Both are utilized for dividing traffic in different directions.

5.2.1 Scoring

Before developing the ACI, sub-indices were scored considering the data value. The detail scoring thresholds are shown in Table 5.2.

Table 5.2. Score matrix of ACI sub-indices

Asset Condition Catalogs (Sectors)	**Asset Condition (Sub-Indices)**	**Scores**		
		3 (Good)	**2 (Moderate)**	**1 (Poor)**
Pavement Condition	IRI (m/km)	<1.5	1.5-2.7	>2.7
	Faulting (mm)	<2.5	2.5-5	>5
	Friction	>60	60-35	<35
	Rutting (mm)	<6	15-6	>15
Pavement Marking	White Marking [WEL+WDL] (mcd/m^2/lux)	>200	200-150	<150
	Yellow Marking [YEL+YCL] (mcd/m^2/lux)	>200	200-100	<100

All of the scores and thresholds were assigned based on the literature review in Chapter 2, with the research team's judgment. As shown in Table 5.2, if a data value of a measure is in the range of the thresholds for good condition, it is scored as 3 points. In the same manner, a data value that indicates poor condition is assigned as 1 point.

As discussed before, the WEL and WDL are grouped in White Marking, while YEL and YCL are incorporated in the Yellow Marking group. To elaborate, the groupings are for the following reasons:

- Marking types in each color have the similar function, as in both white edge lines and white dash lines are used for separating traffic in the same direction, while both yellow edge lines and yellow centerlines are for dividing traffic in different directions
- Different color markings have different retroreflectivity evaluation thresholds, as in white marking is considered in poor condition if the retroreflectivity value is 150 mcd/m^2/lux or lower, while, for yellow marking, the retroreflectivity value is 100 mcd/m^2/lux for poor condition

5.2.2 Weighting

By comparing the simplicity among methods listed in Table 5.1, Equal Weighting and Direct Weighting were selected for this study. All relative weights were assigned directly to sectors and sub-indices, considering their relative significance on highway safety. Figure 5.1 provides an overview of the ACI sector and sub-index calculation layout.

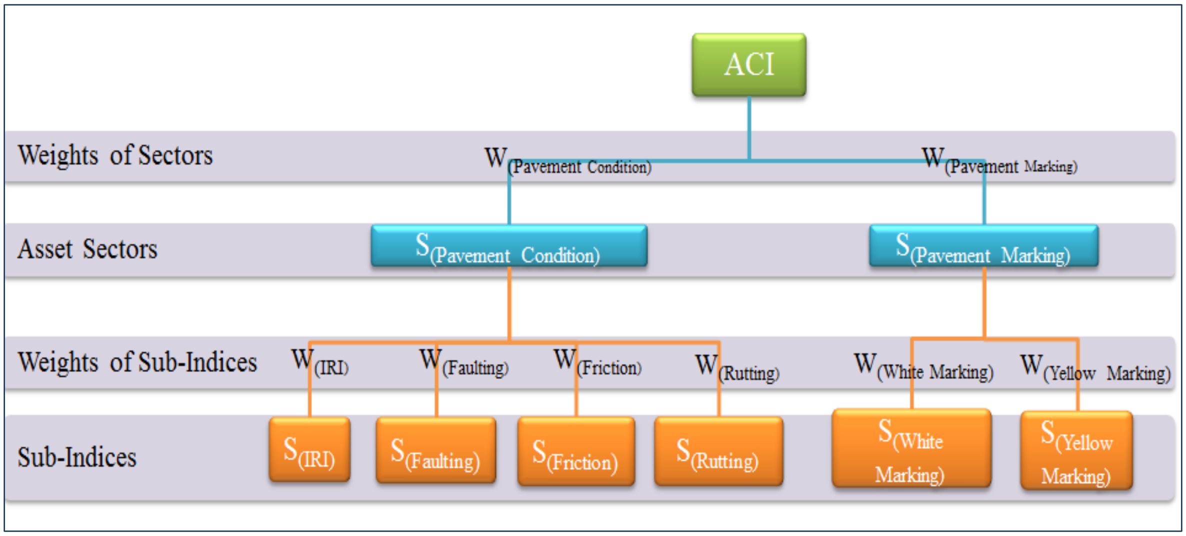


Figure 5.1. ACI sector and sub-index weighting layout

As shown in Figure 5.1, the ACI is estimated by adding the weighted scores of PC and PM. A sensitivity study of the weights was conducted and, based on the literature review, pavement condition is considered to have slightly more effect on roadway safety than pavement marking retroreflectivity, indicating that a higher weight should be assigned to it. Thereby, the weights were assigned as 0.6 for PC and 0.4 for PM.

Each asset condition sub-index, shown along the bottom of Figure 5.1, was scored and weighted first. In a similar manner to sectors, asset condition scores (sub-indices) were weighted according to their significance on safety, and the sector score was calculated by summing all the weighted scores. The following equations (5.1 through 5.3) present the ACI calculations.

$$ACI = \sum_{i=Sectors} S_i \times W_i = S_{PC} \times W_{PC} + S_{PM} \times W_{PM} \quad \textbf{(5.1)}$$

$$S_{PC} = \sum_{i=Sub-indices} S_i \times W_i = S_{IRI} \times W_{IRI} + S_{Faulting} \times W_{Faulting} + S_{Friction} \times W_{Friction} + S_{RD} \times W_{RD} \quad \textbf{(5.2)}$$

$$S_{PM} = \sum_{i=Sub-indices} S_i \times W_i = S_{WM} \times W_{WM} + S_{YM} \times W_{YM} \quad \textbf{(5.3)}$$

where:

$S_{(PC)}$=Score of pavement condition sector
$S_{(PM)}$=Score of pavement marking retroreflectivity sector
$S_{(IRI)}$=Score of IRI
$S_{(Faulting)}$=Score of faulting depth
$S_{(Friction)}$=Score of friction number
$S_{(RD)}$=Score of rutting depth
$S_{(WM)}$=Score of white marking retroreflectivity
$S_{(YM)}$=Score of yellow marking retroreflectivity
$W_{(PC)}$=Weight of pavement condition sector
$W_{(PM)}$=Weight of pavement marking retroreflectivity sector
$W_{(IRI)}$=Weight of IRI
$W_{(Faulting)}$=Weight of faulting depth
$W_{(Friction)}$=Weight of friction number
$W_{(RD)}$=Weight of rutting depth
$W_{(WM)}$=Weight of white marking retroreflectivity
$W_{(YM)}$=Weight of yellow marking retroreflectivity

Under each sector, the sum of weights equals 1. For example, under the PC sector, $W_{IRI} + W_{Faulting} + W_{Friction} + W_{Rd} = 1$.

5.3 Summary

The ACI was developed as a simple, convenient, and understandable indicator for representing the overall physical asset condition of a roadway segment and assisting agencies in the decision-making for pavement preservation and maintenance activities. This chapter presented a step-by-step methodology for calculating a unique condition index of multiple asset conditions that can assist agencies in monitoring asset condition using a convenient indicator.

The ACI contains two general sectors and six sub-indices. Sectors and sub-indices were scored based on available performance and measurement data, and the score thresholds were based on the findings of the literature review. The Equal Weighting and Direct Weighting methods were chosen among the reviewed weighting methods.

The next chapter examines the relationship between the calculated ACI, exposure information (ADT), and number of crashes using statistical models.

6. STATISTICAL ANALYSIS OF CRASH FREQUENCY

This chapter covers the statistical models that were estimated to reveal the relationship between the ACI and safety. The number of crashes, which occurred on each one-mile segment on Iowa primary roads from 2004 through 2009, was estimated by developing a negative binomial regression model. The researchers controlled for exposure by including ADT of the roadway segments as an independent variable in the regression models.

6.1 Descriptive Statistics

6.1.1 ACI

Table 6.1 shows the descriptive statistics for the ACI. Note that the ACI is between 1 and 3, where 1 indicates poor asset condition and 3 indicates good condition.

Table 6.1. Descriptive statistics for the ACI

Moments	
Mean	2.271
Standard Deviation	0.340
Number of Observations	24,052
Skewness	-0.419

As shown in Figure 6.1, the ACI has a left-skewed normal distribution with a mean of 2.27 over the study period.

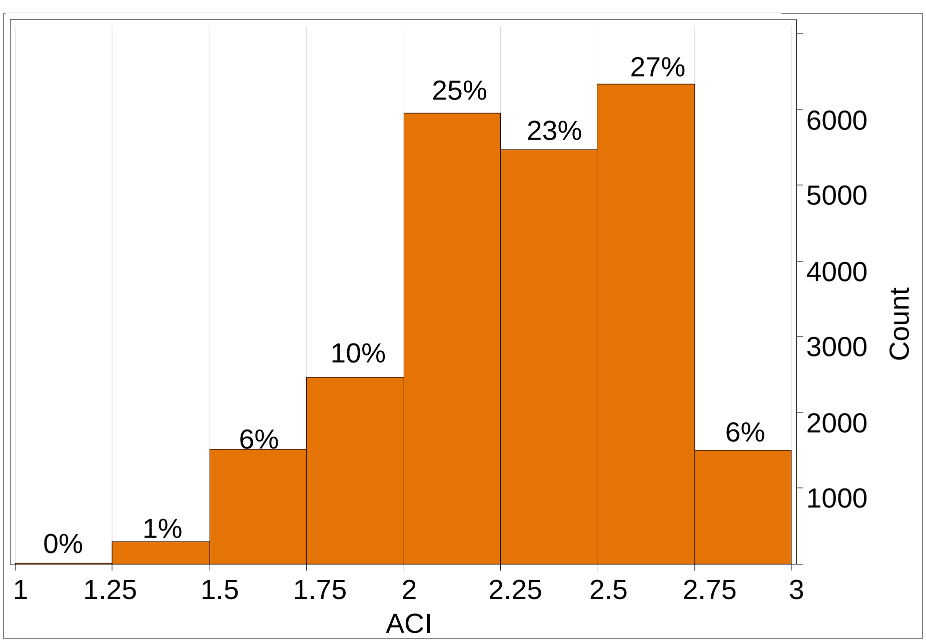


Figure 6.1. Histogram of ACI

Figure 6.2 shows the mean ACI for 2004 through 2009. The mean ACI for all six study years was above 2.0, which represents an overall good condition.

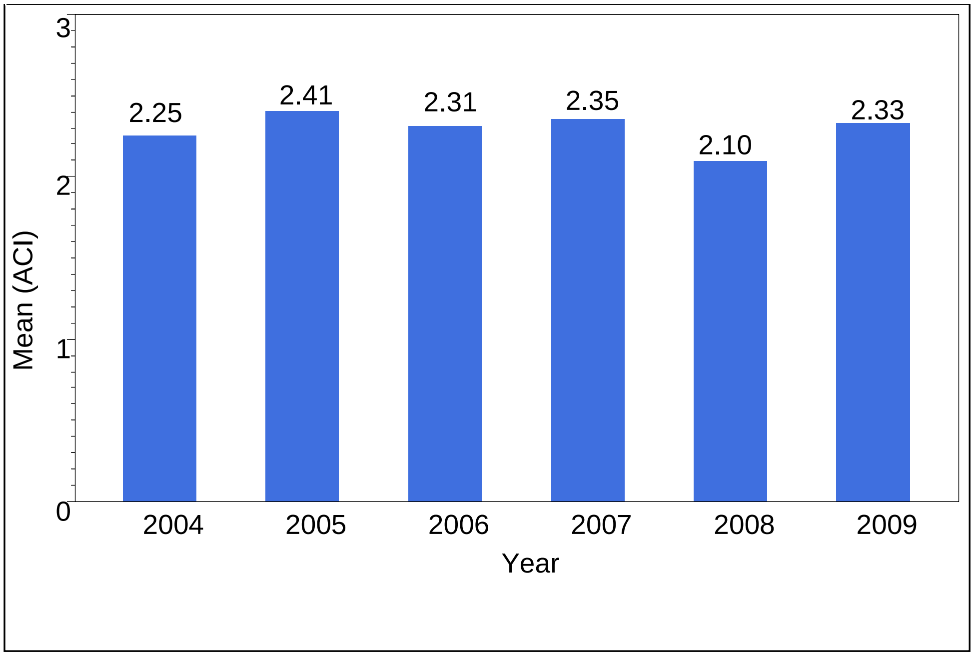


Figure 6.2. Distribution of ACI by year

6.1.2 ADT

Table 6.2 shows the descriptive statistics for ADT.

Table 6.2. Descriptive statistics for ADT

Moments	
Mean	5,758.471
Standard Deviation	8,656.995
Number of Observations	24,052
Skewness	4.287883

The ADT data follows a right-skewed normal distribution as shown in Figure 6.3.

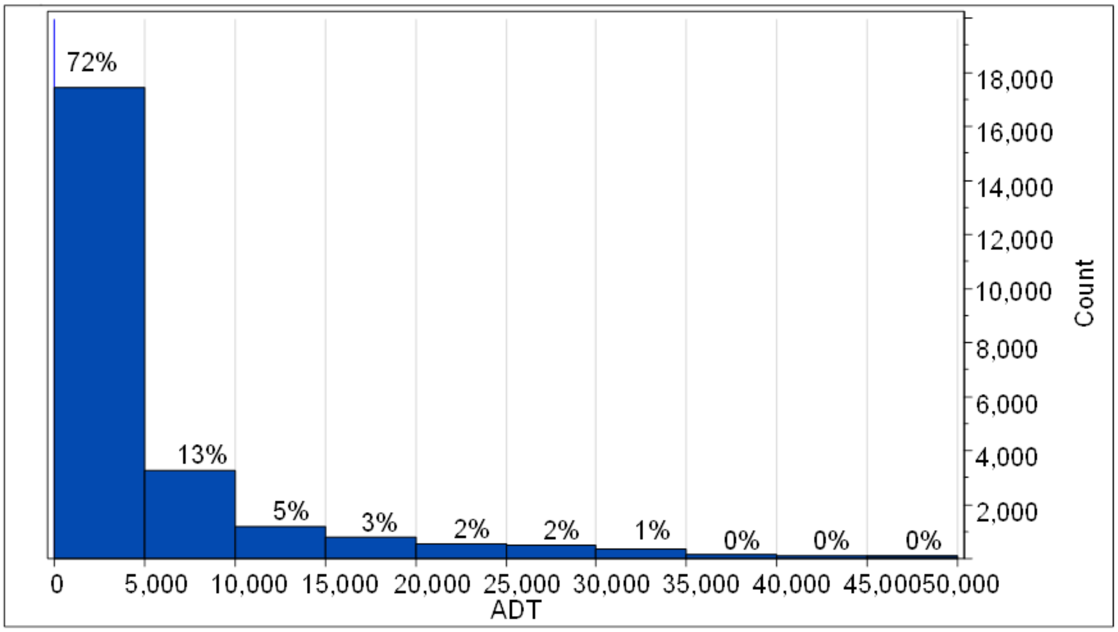


Figure 6.3. Histogram of ADT

As shown in Table 6.2, ADT has a large variance. As such, the natural logarithm of the ADT or Log(ADT), was calculated and used in the models.

6.1.3 Log(ADT)

The descriptive analysis for Log(ADT) is presented in this section. The purpose of converting ADT into Log(ADT) is to change the order of magnitude of ADT so the orders of magnitude of all factors are close enough for estimating a statistic model rationally.

Table 6.3. Descriptive statistics of Log(ADT)

Moments	
Mean	8.069
Standard Deviation	1.003
Number of Observations	24,052
Skewness	0.608

As shown in Table 6.3, the mean of Log(ADT) is about 8.1. The standard deviation (1) is also much smaller than the standard deviation of ADT (8,657), which indicates that the Log(ADT) is much more concentrated around the mean.

The Log(ADT) follows a right-skewed normal distribution, as shown in Figure 6.4, and the skewness is 0.608.

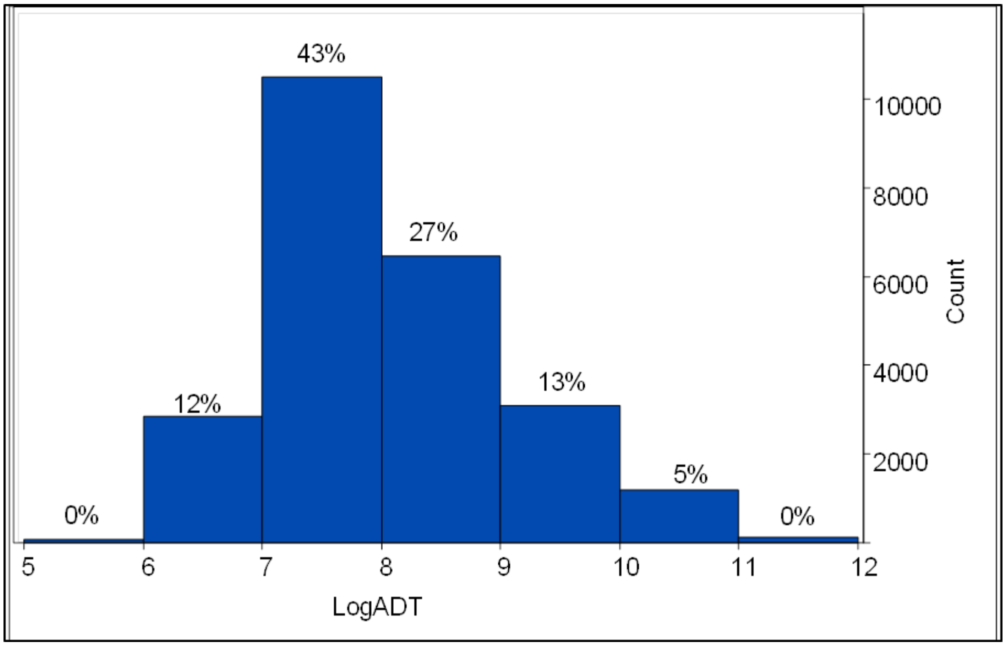


Figure 6.4. Histogram of log(ADT)

As shown in Figure 6.5, the mean ADT for each study year was about 8.0, except for 2007 and 2009, which were closer to 9.3 and 9.4, respectively.

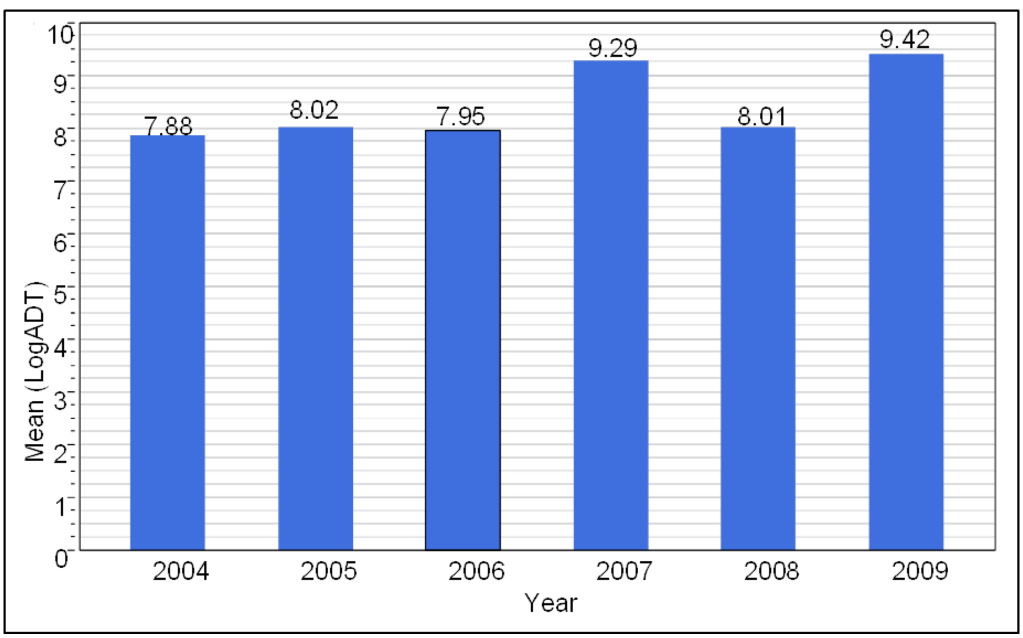


Figure 6.5. Distribution of log(ADT) by year

The reason for these changes in ADT in 2007 and 2009 could be attributed to socio-economic factors at the time or other factors. However, for the purpose of estimating statistical models, these changes are treated as natural variance.

6.1.4 *Number of Crashes*

Table 6.4 shows the descriptive statistics for the number of crashes.

Table 6.4. Descriptive statistics for number of crashes

Moments	
Mean	1.593132
Standard Deviation	3.891348
Number of Observations	24,052
Sum	38,318
Skewness	8.951469

Throughout the six study years, the average number of crashes per mile on Iowa primary roads was about 1.6 per year and the standard deviation shows it could vary ± 3.9 crashes per mile.

The total number of crashes from 2004 through 2009 on Iowa primary roads was more than 38,000; on average 6,386 reported crashes occurred per year, including fatalities, major injury, minor injury, and PDO. Figure 6.6 shows that the distribution of crashes follows a negative exponential distribution, as expected.

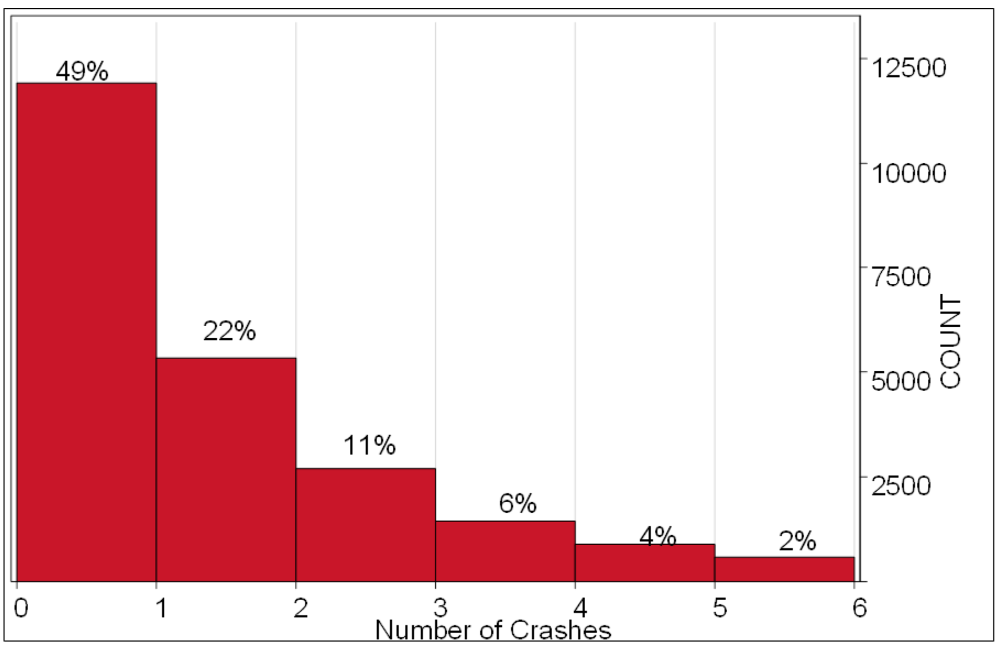


Figure 6.6. Histogram of number of crashes

Figure 6.6 shows that almost half of the study roadway segments have no crashes and 88 percent of the segments had fewer than four crashes.

Figure 6.7 shows the distribution of crashes by year.

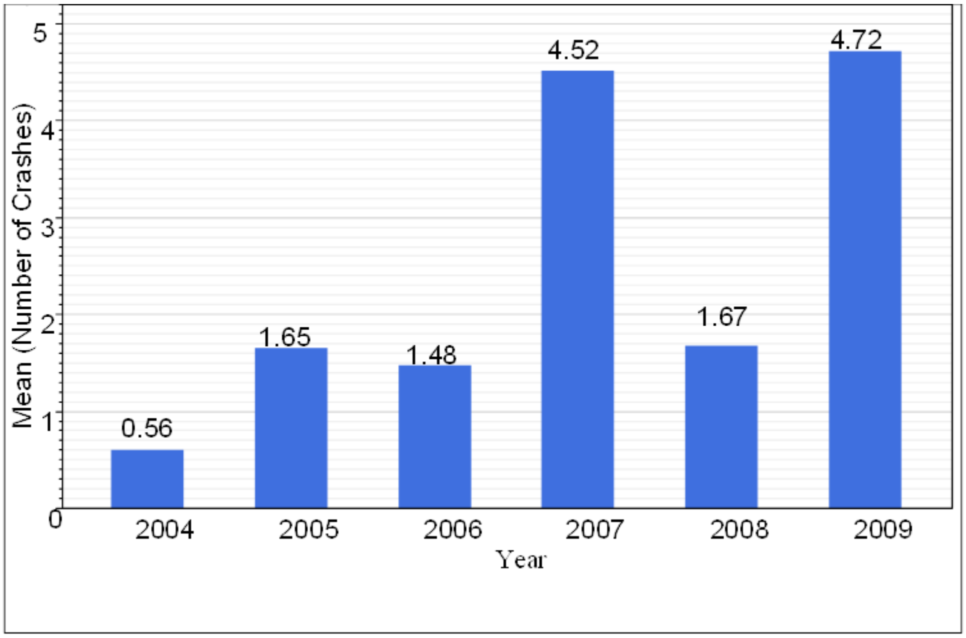


Figure 6.7. Distribution of number of crashes by year

The mean number of crashes in 2004 was the lowest. More crashes occurred in 2007 and 2009. (The mean ADT was higher in 2007 and 2009 as well.)

6.1.5 Correlation Matrix

Before estimating a statistical model of crash frequency as a function of ACI and log(ADT), it was necessary to examine the correlation among the variables. Table 6.5 shows that ACI and log(ADT) are not correlated, so multicollinearity should not be an issue in the model.

Table 6.5. Correlation matrix

	Log(ADT)	**ACI**	**Number of Crashes**
Log(ADT)	1	0.0484	0.3935
ACI	0.0484	1	-0.0169
Number of Crashes	0.3935	-0.0169	1

6.2 Statistical Analysis

6.2.1 Model Selection

One of the research goals was to estimate the relationship between ACI, Log(ADT), and crash frequency. Crash frequency was selected as the dependent variable.

Given the numbers of crashes represent count data, negative binomial and Poisson were considered as regression model candidates. One requirement of the Poisson model is that mean of the count process equals its variance; if its variance is significantly larger than the mean, the data are over dispersed and modeled more appropriately by the negative binomial.

To choose the more suitable model, the variance and the mean were compared as shown in Equation 6.1.

$$(\text{Variance}_{\text{number of crashes}} = 15.14) > (\text{Mean}_{\text{number of crashes}} = 5.19) \quad \textbf{(6.1)}$$

Given the crash data are over dispersed, the negative binomial model was chosen.

6.2.2 Negative Binomial Model

The negative binomial model is derived by rewriting Equation 6.2 such that, for each observation, i, crash frequency λ_i is estimated as follows:

$$\lambda_i = e^{\sum \beta \chi_i + \varepsilon_i} \quad \textbf{(6.2)}$$

where: e^{ε_i} is a Gamma-distributed disturbance term with mean = 1 and variance = α . This model has an additional parameter, α, which is often referred to as the overdispersion parameter, such that:

$$VAR[y_i] = E[y_i]\big[1 + \alpha E[y_i]\big] = E[y_i] + \alpha E[y_i]^2 \quad \textbf{(6.3)}$$

This α is a criterion of selecting between Poisson and negative binomial regression. The α perimeter indicates the overdispersion parameter. The negative binomial distribution has the form shown in Equation 6.4:

$$P(y_i) = \frac{\Gamma\big((1/\alpha) + y_i\big)}{\Gamma(1/\alpha) y_i!} \left(\frac{1/\alpha}{(1/\alpha) + \lambda_i}\right)^{1/\alpha} \left(\frac{\lambda_i}{(1/\alpha) + \lambda_i}\right)^{y_i} \quad \textbf{(6.4)}$$

where: $\Gamma(.)$ is a gamma function (Washington et al., 2011).

The models were estimated using the statistical program Limdep (Greene 2007).

Table 6.6 shows the negative binomial model estimation results. The model outputs are presented in Appendix A. It was found that crash frequency increases with exposure and, the higher the ACI, the fewer crashes expected. These results are in line with the research team's a priori expectations.

Table 6.6. Negative binomial model estimation results

Variable Description	Estimated Parameter	t-Statistic
Constant	-5.381	-135.919
Log(ADT)	0.771	226.502
ACI	-1.291	-16.713
Number of Observations, *N*	28.835	
Restricted Log-likelihood, *LL(0)*	-61707.76	
Log-likelihood at convergence, *LL(β)*	-45714.20	
Chi-square, χ^2	31,987.11	
Rou-square, ρ^2	0.259	

After checking by both ρ^2 –value and χ^2 –value, it could be determined that the model is statistically significant (Washington, Karlaftis and Mannering 2011). The chi-square value for α=0.001 and three parameters is $\chi^2_{3,0.0001} = 21.1075$, which is much smaller than 31,987.11; thus, the model is statistically significant.

6.2.3 Sensitivity Analysis of Weights

The researchers conducted a sensitivity analysis to assess how the variation (uncertainty) in the output of the statistical model can be attributed to different variations in the weights. Nine weight combinations/groups were generated (including the default group) for sensitivity analysis, as shown in Table 6.7.

Table 6.7. Sensitivity analysis of weights

	Weights							
	Marking		Pavement Condition				Asset Condition	
Group	**White**	**Yellow**	**IRI**	**Faulting**	**Friction**	**Rutting**	**Marking**	**Pavement Condition**
A (default)	0.4	0.6	0.2	0.2	0.3	0.3	0.5	0.5
B	0.5	0.5	0.2	0.2	0.3	0.3	0.5	0.5
C	0.3	0.7	0.2	0.2	0.3	0.3	0.5	0.5
D	0.6	0.4	0.2	0.2	0.3	0.3	0.5	0.5
E	0.7	0.3	0.2	0.2	0.3	0.3	0.5	0.5
F	0.4	0.6	0.25	0.25	0.25	0.25	0.5	0.5
G	0.4	0.6	0.2	0.2	0.3	0.3	0.4	0.6
H	0.4	0.6	0.2	0.2	0.3	0.3	0.6	0.4

Group A is the default group and all weights in this group were obtained from the literature review. The other groups were created based on Group A by increasing or decreasing the weights.

By comparing models among groups, the researchers assessed the sensitivity and variation of weights. For example, Group B and C have all the same weights as Group A, except for the weights for White Marking and Yellow Marking.

In addition, after estimating statistical (negative binomial regression) models relating crash frequency and ACI for each of the groups of weights and comparing the resulting coefficients, the researchers could assess the combinations of weights that are most suitable. Table 6.8 shows the results of the statistical analysis.

Table 6.8. Statistical model estimation results for sensitivity study

	Descriptive Analysis			Models (dependent variable: crash number)				
						Negative Binomial estimation results		
Gp.	**Mean (crash per mile - year)**	**Std. Dev. (crash per mile - year)**	**Observations (#)**	**R^2**	**Observations (#)**	**constant**	**β_{ACI}**	**t-statistic**
A	2.27	0.34	24,584	0.259	24,425	0.799	-0.134	-6.233
B	2.27	0.35	24,584	0.259	24,425	0.941	-0.197	-8.668
C	2.26	0.34	24,584	0.259	24,425	1.120	-0.277	-8.149
D	2.28	0.35	24,584	0.260	24,425	0.844	-0.153	-6.904
E	2.28	0.36	24,584	0.260	24,425	0.75	-0.111	-5.17
F	2.25	0.34	24,584	0.251	24,425	0.741	-0.123	-5.161
G	2.28	0.39	24,584	0.260	24,425	0.761	-0.116	-5.827
H	2.25	0.31	24,584	0.258	24,425	1.409	-0.408	-9.809

The coefficients of determination of all statistical models are about 0.385, so it can be concluded that the models are not sensitive to the weights of the sectors and sub-indices, and the default weight combination in Group A is rational and powerful enough to represent the relative significances both between sectors and among sub-indices.

6.2.4 Transferability Test

Figure 6.8 shows the predicted crash frequency with respect to ACI. Crash frequency is higher for ACI values between 1 and 1.5. As such, the researchers examined whether it is statistically significant to estimate separate models for different ACI ranges. The results of this test are presented next.

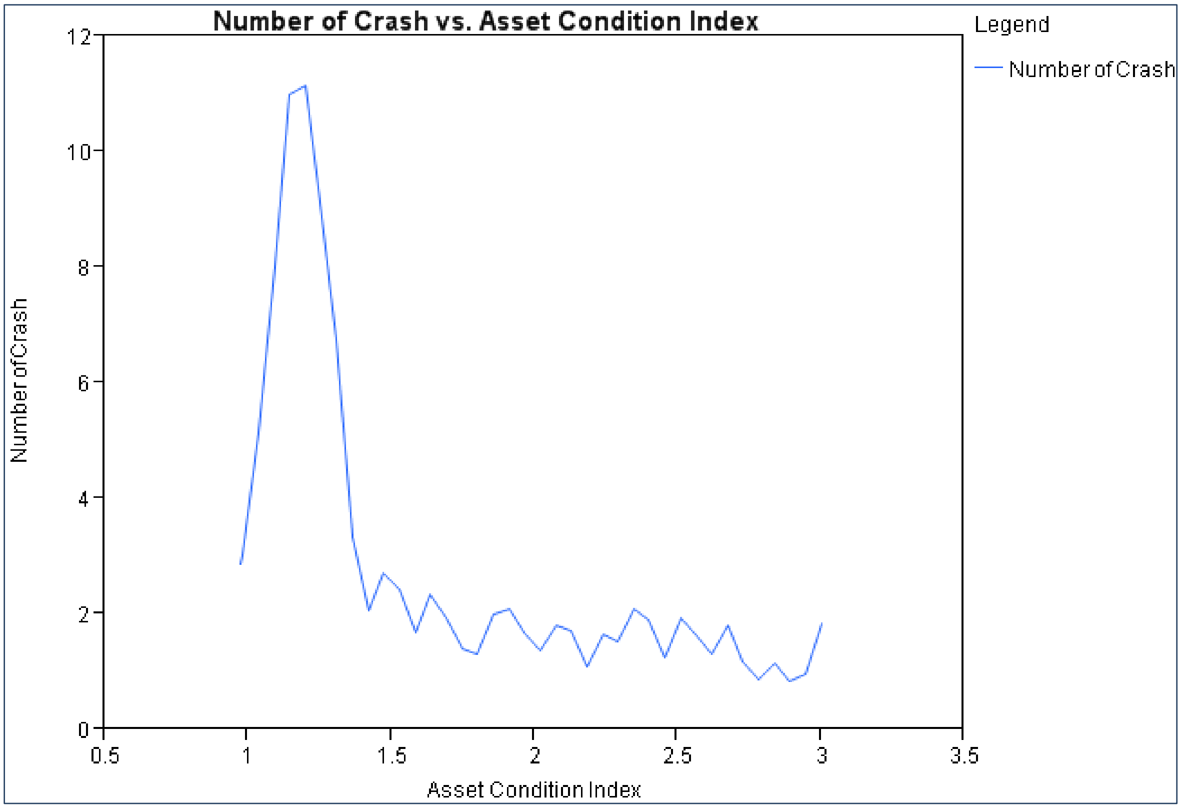


Figure 6.8. Predicted crash frequency versus ACI

The likelihood ratio test (Washington et al. 2011), which is also called the transferability test, was conducted to determine whether separate models for different ACI ranges were statistically significant. This test was conducted using the same variables in all three models (all data, ACI lower than or equal to 1.5, and ACI higher than 1.5) as shown in Equation 6.5 (Bahar, et al. 2006):

$$\chi^2 = -2\left(LL_\beta - LL_{\beta_a} - LL_{\beta_b}\right) \quad \textbf{(6.5)}$$

where:

LL_β is the likelihood at convergence of the model estimated with the data from both regions (all data)

$LL_{\beta a}$ is the log-likelihood at convergence of the model using region *a* data (ACI lower than or equal to 1.5)

$LL_{\beta b}$ is the log-likelihood at convergence of the model using region *b* data (ACI higher than 1.5)

Table 6.9 shows the estimation results of this test. The resulting χ^2 statistic showed that it was statistically significant to estimate two separate models.

Table 6.9. Transferability test estimation for ACI ranges

	All data **(LL_{β})**	**ACI≤1.5** **(LL_{β_a})**	**ACI>1.5** **(LL_{β_b})**	χ^2	$\chi^2_{0.0001,4}$
Log-likelihood at Convergence $LL_{(\beta)}$	-45,714.20	-1,999.84	-43,570.57	287.59	23.5127
Number of parameters	4	4	4		

6.2.5 Final Models

Table 6.10 shows the final negative binomial model estimation results for crash frequency as a function of log(ADT) and ACI lower than or equal to 1.5 or higher than 1.5. The model outputs are presented in Appendix A.

Table 6.10. Summary of separate negative binomial models

	ACI≤1.5		**ACI>1.5**	
Variables	**Coefficient**	**t-test**	**Coefficient**	**t-test**
Constant	-0.780	-11.776	-5.761	-79.495
ACI	-1.668	-20.708	-0.179	-7.905
Log(ADT)	0.316	42.05	0.784	137.986
ρ^2	0.500		0.242	
Number of observations	906		27,929	

The final model for ACI≤1.5 is shown in Equation 6.6:

$$Number\ of\ Crashes_{ACI\leq 1.5} = e^{-0.7799-1.6679\times ACI+0.3162\times LogADT} \quad \textbf{(6.6)}$$

The final model for ACI>1.5 is shown in Equation 6.7:

$$Number\ of\ Crashes_{ACI>1.5} = e^{-5.761-0.179\times ACI+0.784\times LogADT} \quad \textbf{(6.7)}$$

The overall ρ^2-values for these models are 0.500 and 0.242, respectively. The model for segments with ACI lower than or equal to 1.5 shows a relatively higher fit, most likely because of the smaller number of observations. In addition, comparing to the previous model, on all the data (Table 6.6) the suitability of fit is superior.

All parameter coefficients in both separate models have the expected signs (+ or –, positive or negative, or increase or decrease). Comparing the two models, the absolute value of the coefficient of ACI is higher in the model for segments with ACI≤1.5, while the coefficient of Log(ADT) is relatively lower. This means, for road segments with an ACI lower than or equal to 1.5, the ACI has a greater effect on safety.

6.3 Summary

The researchers used negative binomial models to predict the relationship between crash frequency and the ACI. The estimation results indicated that the higher the ACI of a roadway segment, the lower the number of crashes expected. In addition, the higher traffic exposure Log(ADT) on a roadway segment, the higher the number of crashes expected.

The sensitivity analysis of weights revealed that the statistical model estimation results relating crash frequency to ACI were not sensitive to the assumed weights of ACI sectors and sub-indices. These results suggested that the default assumptions (based on the literature review) could be adopted.

In addition, the transferability test showed that separate negative binomial models for different ACI ranges better explain the relationship between crash frequency, ACI, and Log(ADT). The researchers found that the effect of ACI on crash frequency on roadway segments with ACI lower than or equal to 1.5 was higher and, as such, these segments should have priority for preservation or maintenance.

7. EVALUATION OF ASSET TREATMENT STRATEGIES

This chapter describes the methodology used to evaluate six different pavement condition or pavement marking improvement strategies in terms of economic efficiency and crash reduction and the corresponding results.

The estimated results using the models presented in the last chapter were used to assess the economic feasibility of these treatment strategies, so that agencies can utilize the information to select projects and make better decisions.

Economic efficiency was evaluated using two methods: single-year benefit-cost ratio (BCR) analysis and five-year net present value (NPV) analysis, one year and five years after implementing alternative treatment strategies, respectively. Benefits represent safety improvements in terms of crash reduction.

7.1 Goal of the Evaluation

The goal of this evaluation is to develop a method for selecting asset treatment strategies that have an impact on both asset condition and safety in terms of crash reduction. The one-year BCR analysis and five-year NPV analysis were adopted for different study periods in a bid to prioritize the treatment strategies in the short and long term.

7.2 Treatment Alternatives

The researchers selected and grouped six improvement treatments into the three that would improve pavement condition and the three that would improve pavement marking. PC treatment improvement alternatives included pavement reconstruction, major rehabilitation, and minor rehabilitation. The three PM material replacement types selected were regular paint, durable material marking, and tape markings.

7.2.1 Pavement Condition Alternatives

The selection of a treatment strategy among reconstruction, major rehabilitation, and minor rehabilitation is based on current pavement condition, target level of service, and budget constraints.

Pavement reconstruction involves the complete removal of an existing pavement to the sub-grade and construction of a new pavement structure. This most expensive strategy is usually needed when the existing pavement has deteriorated to a condition that cannot be salvaged with corrective action (MassDOT 2006). The estimated unit cost of this type of pavement treatment is approximately $1,000,000/mile. Service life of a pavement after reconstruction is expected to be 20 years.

Pavement rehabilitation, which is a major activity for all highway agencies, can be defined as a structural or functional pavement enhancement that produces a substantial extension in service life by substantially improving pavement condition and ride quality (Hall et al., 2001).

When selecting a rehabilitation strategy, agencies select the most cost-effective rehabilitation strategy given a set of criteria, which may include reduced service life, life-cycle cost, and budgetary constraints. According to the current pavement condition, different rehabilitation strategies can be selected for different types of pavement, distress types, levels of rehabilitation, and target service life extension.

Major rehabilitation can be selected when maintenance is needed on the pavement structure, relatively-more serious distresses are observed, or longer service life extension is expected. The cost of this type of work is estimated as $500,000/mile and life cycle is assumed to be 10 years.

On the other hand, minor rehabilitation involves surface overlaying, repairing joints, and some other relatively smaller maintenance operations. The cost of this type of work is approximately $150,000/mile, and its life cycle is assumed to be three years.

7.2.2 Pavement Marking Alternatives

Three types of pavement marking materials were selected as pavement marking replacement alternatives: regular paint, durable marking, and tape markings. These alternatives are currently used by the Iowa DOT on different types of marking lines.

Regular paint is the most commonly used treatment among agencies. More than 95 percent of Iowa roadways are marked using fast-drying waterborne paints. Regular paint costs relatively less than other types of markings; however, life cycle is also typically shorter.

As mentioned in the Chapter 4, the Iowa DOT repaints pavement markings twice per year, in spring and fall, so the service life of this type of marking is assumed to be half a year. The cost of regular paint marking is assumed to be $1,188/mile.

Durable markings are expected to have relatively longer service lives than regular paint and, as a result, have higher cost-effectiveness or lower life-cycle cost than regular paint. The Iowa DOT started to evaluate and utilize durable waterborne paints with glass beads, which are considered durable marking, in 2005.

Given the need in Iowa for snow plowing (due to winter weather), pavement markings can deteriorate significantly. The estimated unit cost of durable marking is $11,880/mile and the service life is assumed to be two years. (The cost of winter maintenance is not taken into account in this unit cost.)

Tape marking is used typically as a transverse marking material (e.g., crosswalks, stop bars). Tape marking performs well on both portland cement concrete (PCC) and asphalt cement concrete (ACC) pavements (Thomas and Schloz 2001).

In general, tape marking has a high initial cost; however, tape marking is relatively easy to install and has relatively long durability, depending on the placement location. In addition, when tape is installed on new ACC pavement sections, the road can be open to traffic as soon as the pavement is ready. Tape marking provides the additional advantage of avoiding the need for temporary marking materials because it can be installed immediately after construction is complete (and not have to wait up to two weeks for installation).

The estimated unit cost of tape marking is $47.520/mile and the service life is assumed to be five years.

7.3 Relative ACI Improvement and Depreciation Rate

Before conducting the economic analysis, each treatment alternative was assigned a relative improvement value on the ACI scale of 0 to 3. The relative improvement values were estimated considering the alternative's impact on safety in terms of reducing crash frequency, as documented in the literature. Given that ACI is an index between 1 and 3, the improved ACI cannot be higher than 3 regardless of initial condition.

AC depreciation is an important consideration for monitoring, performance measuring, and pavement life-cycle cost analysis. This study considers AC depreciation and straight-line depreciation in the five-year NPV analysis.

In the previous chapter, it was shown that roadway segments with ACI lower than or equal to 1.5 have relatively higher crash frequency. Thus, 1.5 is considered as a critical value of ACI. Based on straight-line depreciation, the depreciation rate is calculated as shown in Equation 7.1:

$$Depreciation\ Rate = \frac{ACI_{optimal} - ACI_{critical}}{Service\ Life} = \frac{3.0 - 1.5}{Service\ Life} = \frac{1.5}{Service\ Life} \quad \textbf{(7.1)}$$

The relative improvement values for treatment alternatives, respective costs, service lives, and depreciation rates are shown in Table 7.1.

Table 7.1. Attributes of treatment alternatives

Treatment Alternatives	Price (per mile)	Relative Improvement of ACI	Service Life (years)	Depreciation Rate
Maintenance				
Reconstruction	$1,000,000.00	2	20	0.075
Major Rehab	$500,000.00	1	10	0.15
Minor Rehab	$150,000.00	0.5	3	0.5
Replacement				
Regular Paint	$1,188.00	0.01	0.5	3
Durable Markings	$11,880.00	0.05	2	0.75
Tape Markings	$47,520.00	0.2	5	0.3

7.4 Identifying Costs and Benefits

The unit costs (price per mile) of treatment alternatives are identified and presented in Table 7.1. Given the costs are expressed in dollars per mile, and each data row represents a one-mile road segment, costs for each alternative on each segment is the same as the unit cost.

However, the costs are the capital costs that were invested in the first year of the project, while the study periods in this research are one year and five years, so these capital costs need be converted into equivalent uniform annual cost (EUAC).

Safety benefits in this analysis are measured as the improvement in crash reduction cost from each alternative treatment. The statistical models (presented in Chapter 6) showed that the number of crashes would decrease when the ACI is higher. Therefore, it is expected that, after implementing the six ACI improvement alternatives, number of crashes on each treated road segment should decrease.

The economic cost of crashes, which is borne by individuals, insurance companies, and government, consists of property damage, loss of household productivity, loss of market productivity, and workplace costs.

Intangible costs include pain and suffering, and loss of life. In addition to the nation-wide crash cost estimates, each state government has its own crash cost estimate table. In this study, the researchers used the crash costs in Iowa, shown in Table 7.2, to monetize the safety benefits of the treatment strategies given expected crash reduction.

Table 7.2. Iowa crash costs in 2007

Collision Type	Crash Cost
Fatal	$3,500,000
Disabling Injury	$240,000
Evident Injury	$48,000
Possible Injury	$25,000
PDO	$2,700

The crash cost values shown in Table 7.2 are provided by crash severity, so the reduction in the number of crashes need to be distributed by severity as well. Table 7.3 shows the distribution of crashes by crash severity for each study year and on average over the six-year study period.

Table 7.3. Distribution of crashes by severity

		Severity				
		Fatal	**Disabling Injury**	**Evident Injury**	**Possible Injury**	**PDO**
2004	Percentage	1.1%	4.1%	11.8%	18.8%	64.2%
	Counts	125	473	1,354	2,159	7,367
2005	Percentage	1.4%	4.5%	11.4%	20.1%	62.6%
	Counts	167	541	1,369	2,406	7,496
2006	Percentage	1.4%	4.2%	11.9%	19.7%	62.7%
	Counts	151	443	1,266	2,089	6,652
2007	Percentage	1.3%	3.7%	11.3%	18.7%	65.1%
	Counts	161	470	1,439	2,389	8,330
2008	Percentage	1.0%	2.9%	3.1%	35.8%	57.1%
	Counts	157	437	469	5,366	8,571
2009	Percentage	1.2%	3.5%	10.9%	18.6%	65.9%
	Counts	115	348	1,071	1,829	6,493
Total	Percentage	1.2%	3.8%	9.7%	22.6%	62.6%
	Counts	876	2,712	6,968	16,238	44,909

The researchers assumed that the reduction in the number of crashes would follow a similar distribution to that shown in the last two rows of Table 7.3

7.5 Single-Year Benefit-Cost Ratio (BCR) Analysis

The single-year BCR analysis investigated which improvement alternative would achieve the highest BCR one year after implementation of the treatment strategy as follows:

1. Calculate improved ACI using the relative improvement for each alternative treatment (Table 7.1)

2. Predict the number of crashes expected on the segment given the new ACI (Table 6.10)

3. Calculate the reduction in the annual number of crashes because of the improvement in ACI terms (scale of 0 to 3)

4. Calculate the reduction in the annual number of crashes by severity (Table 7.3)

5. Monetize safety benefits by multiplying crash costs (Table 7.2) and reduction in the annual number of crashes by severity

6. Calculate the total annual cost benefits of the alternative in 2007 dollars

7. Convert to 2011 dollars using a discount rate (*i*) of 4% as shown in Equation 7.2:

$$Benefit_{2011} = Benefit_{2007} \times (1+i)^4 \quad \textbf{(7.2)}$$

8. Convert cost into EUAC as shown in Equation 7.3 (where *i*=4%):

$$EUAC_{Alt.i} = Cost_{Alt.i} \times \left[\frac{i(i+1)^{Service\ Life}}{(1+i)^{Service\ Life} - 1}\right] \quad \textbf{(7.3)}$$

9. Calculate NPV and BCR as shown in Equations 7.4 and 7.5:

$$NPV_{Alt.i} = Benefit_{Alt.i} - EUAC_{Alt.i} \quad \textbf{(7.4)}$$

$$B/C_{Alt.i} = \frac{Benefit_{Alt.i}}{EUAC_{Alt.i}} \quad \textbf{(7.5)}$$

As shown in Table 7.4, minor rehabilitation has the highest BCR among all alternatives, and durable material marking holds the highest BCR among the pavement marking treatments. As a result, if considering only one year after implementation, minor rehabilitation appears as the most-economic alternative for improving asset condition and safety in terms of crash reduction.

Table 7.4. NPV and BCR of treatment alternatives one year after implementation

	Economics	
Alternatives	**NPV**	**BCR**
Reconstruction	$38,650.53	1.525
Major	$50,217.62	1.815
Minor	$55,743.38	2.031
Paint	$482.44	1.195
Durable	$4,850.66	1.770
Tape	$4240.80	1.400

7.6 Five-Year Net Present Value (NPV) Analysis

This analysis evaluated the alternatives over a longer study period (five years), considering both asset condition depreciation and time value of money.

Before calculating ACIs and predicting numbers of crashes, the dataset was divided into six ranges based on ACI as follows:

$ACI \leq 1.5$
$1.5 < ACI \leq 2.00$
$2.0 < ACI \leq 2.25$
$2.25 < ACI \leq 2.50$
$2.5 < ACI \leq 2.75$
$2.75 < ACI \leq 3.00$

By breaking the dataset into ranges, the results would provide recommendations among alternatives based on the current ACI and make the project selection process more practical and feasible.

A similar procedure to that outlined in the last section was adopted. In addition, the change in ACI over five years was estimated using the depreciation rate. Meanwhile, the alternatives with service lives shorter than five years would be implemented again in the following year after the service life. This procedure was applied to each of the six ACI ranges.

Table 7.5 and Figure 7.1 show the analysis results for major rehabilitation on segments with ACI ranging from 1.5 to 2.0. All the results are shown in Appendix B.

Table 7.5. Reduction in crash frequency and NPV for major rehabilitation on segments with 1.5 < ACI ≤ 2.00

	Average Number of Crashes					
Year	**Non-Treated**	**Treated**	**Reduced**	**Benefit**	**Cost (EUAC)**	**NPV**
0	0	0	0	-	$61,645.47	$-61,645.47
1	0.2409	0.0741	0.1668	$12,316.02	$61,645.47	$-47,432.17
2	0.4629	0.0884	0.3745	$27,651.97	$61,645.47	$-31,428.91
3	0.988	0.1055	0.8825	$65,161.18	$61,645.47	$3,125.45
4	2.011	0.1259	1.8851	$139,190.18	$61,645.47	$66,285.54
5	3.5365	0.1503	3.3862	$250,026.94	$61,645.47	$154,835.84
					NPV	$83,740.28

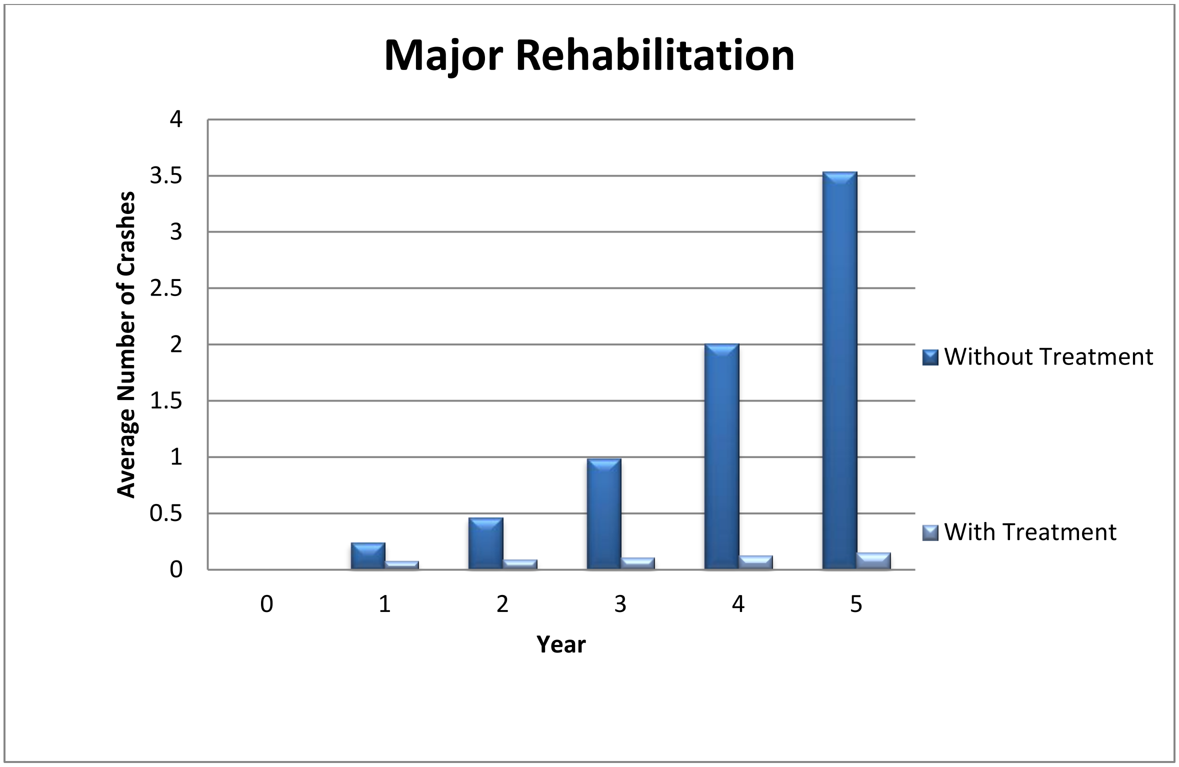
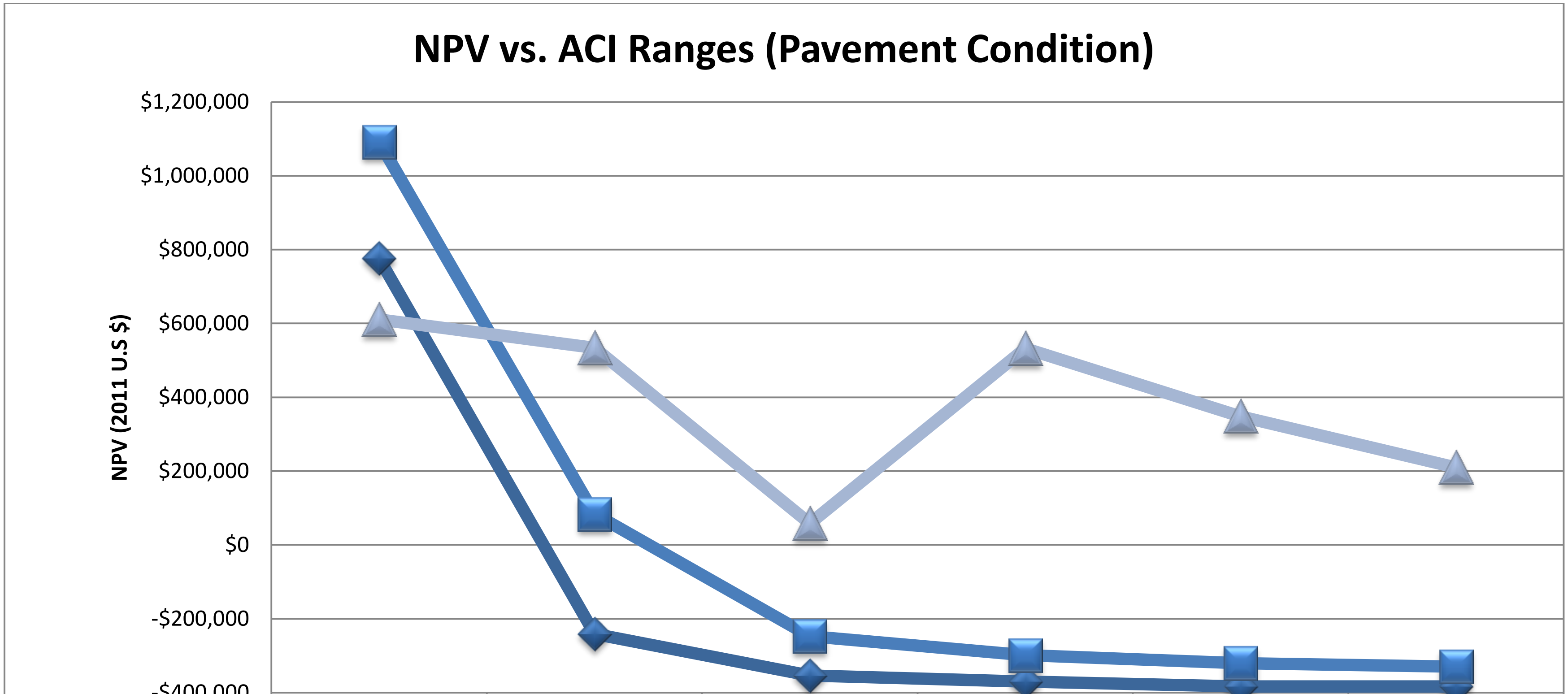


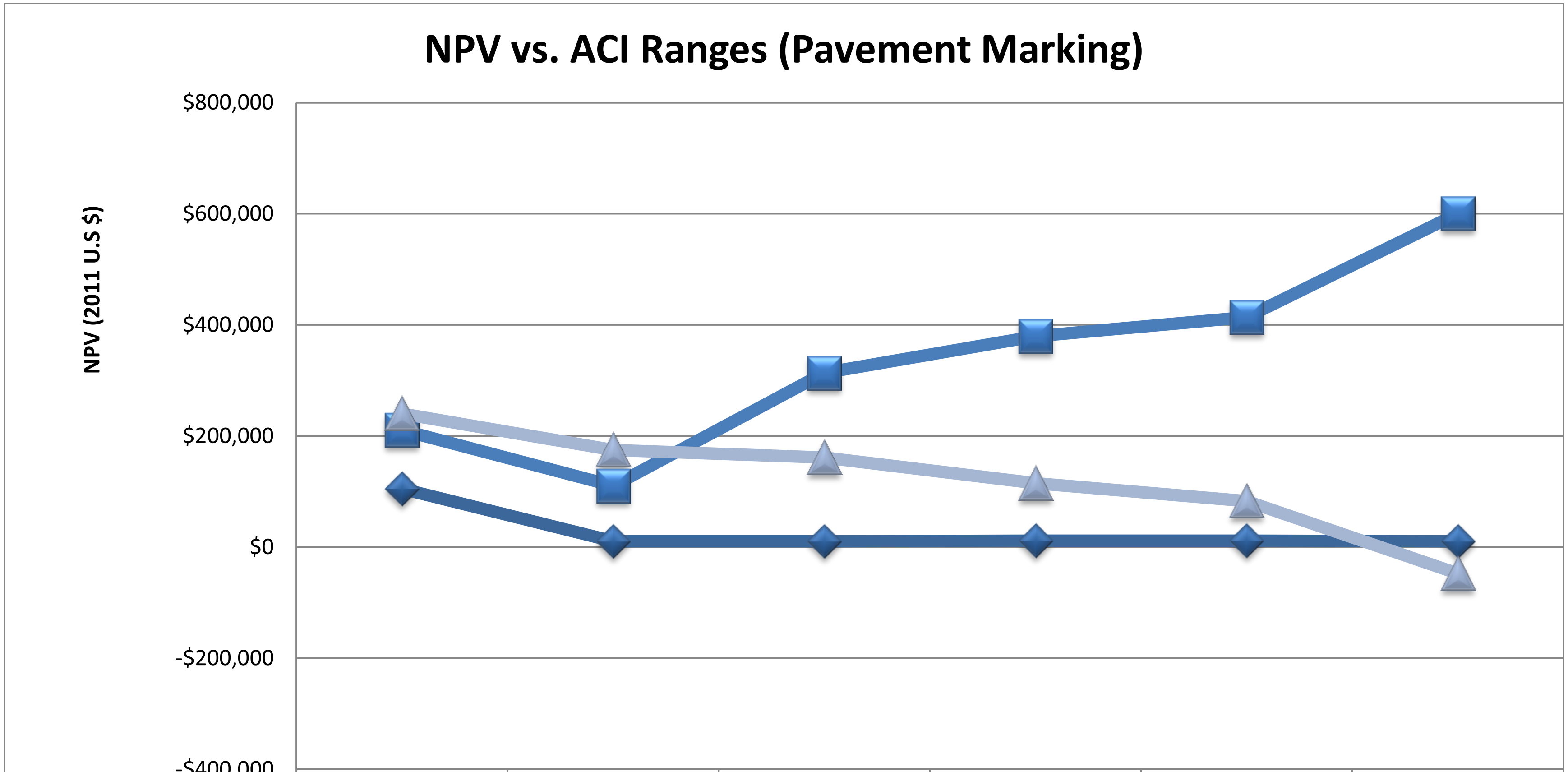
Figure 7.1. Crash trends before and after treatment

Figures 7.2 and 7.3 show the summary of the NPV analysis for the three alternatives by ACI range. The researchers observed that for different ACI ranges (1.5 to 3), the recommended alternative, which is the one with the highest NPV, may change, particularly for the two lowest ACI ranges (1.5 to 2.0).



	ACI≤1.50	1.50<ACI≤2.00	2.00<ACI≤2.25	2.25<ACI≤2.50	2.50<ACI≤2.75	2.75<ACI≤3.00
Reconstruction	776,676.51	-241,381.06	-353,625.25	-370,103.21	-383,279.32	-383,279.32
Major	1,092,326.69	83,740.28	-247,205.25	-298,399.11	-320,636.58	-329,375.24
Minor	610,903.09	534,122.00	58,034.25	532,496.94	347,850.45	209,691.47

Figure 7.2. NPV for pavement condition group alternatives by ACI range



	ACI≤1.50	1.50<ACI≤2.00	2.00<ACI≤2.25	2.25<ACI≤2.50	2.50<ACI≤2.75	2.75<ACI≤3.00
Paint	104,929.66	10,241.30	10,706.02	11,347.67	11,738.71	10,234.25
Durable Material	210,563.54	110,273.72	313,610.75	379,476.41	413,977.49	600,445.70
Tape	240,378.69	174,719.46	161,123.49	114,873.28	82,830.31	-47,855.48

Figure 7.3. NPV for pavement marking group alternatives by ACI range

For segments with an ACI higher than 2.0, minor rehabilitation to improve pavement condition is more cost-effective than the other strategies, while durable markings are more cost-effective than the other treatments to improve pavement marking condition. For segments with an ACI between 1.5 and 2.0, minor rehabilitation and tape marking are recommended, while for segments with an ACI lower or equal to 1.5, major rehabilitation and tape markings are the preferred alternatives.

7.7 Summary

In this chapter, the single-year BCR analysis and five-year NPV analysis were presented. Both short-term and long-term safety benefits in terms of crash reduction costs and treatment costs were estimated for six alternative treatment strategies.

Minor rehabilitation and durable marking are recommended as more cost-effective treatment alternatives in the short-term. In the long-term, the same recommendation holds for segments with an ACI higher than 2.0. For segments with an ACI lower than 1.5, major rehabilitation and tape marking are highly recommended.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 Research Summary

This analysis studied the relationship between asset performance and safety performance on rural Iowa primary roads. To achieve this analysis, the researchers used route milepost-based integration to integrate the crash and condition data of the roadway segments, developed a methodology to estimate a composite asset condition index (ACI), estimated statistical models of crash frequency as a function of ACI, while controlling for traffic exposure (ADT), and examined the economic feasibility of six asset condition-improving strategies using economic analysis approaches.

8.2 Key Findings

8.2.1 Estimation of Asset Condition Index

The ACI was developed as a simple, convenient, and easy-to-understand indicator for representing the overall physical asset condition of a roadway segment and assisting agencies in decision-making for pavement preservation and maintenance activities.

The researchers developed a step-by-step methodology for calculating the unique condition index using multiple asset condition measures. The methodology involved scaling and weighting asset condition components, such as pavement condition and pavement retroreflectivity, as well as their subcomponents. The resulting ACI values range from 1 (indicating poor condition) to 3 (indicating good condition).

8.2.2 Statistical Analysis

Negative binomial models were estimated to predict the relationship between crash frequency and ACI, while accounting for exposure (ADT). The estimation results indicated that the higher the ACI of a roadway segment, the lower the expected number of crashes.

In addition, the researchers found that separate negative binomial models for different ACI ranges explain the relationship among crash frequency, ACI, and exposure (ADT) better than a single model. The impact of ACI on crash frequency for roadway segments with an ACI lower or equal to 1.5 was higher compared to that for roadway segments with an ACI higher than 1.5.

8.2.3 Economic Analysis

Both short-term and long-term safety benefits in terms of crash reduction along with treatment costs were estimated for six alternative treatment strategies via a single-year BCR analysis and a five-year NPV analysis.

Minor rehabilitation and use of durable pavement marking materials are recommended as more cost-effective treatment alternatives in the short-term. In the long-term, the same recommendation holds for segments with an ACI higher than 2.0. For segments with an ACI lower than 1.5, major rehabilitation and tape marking are recommended.

8.3 Study Limitations

There are some limitations pertaining to this study, as discussed below.

8.3.1 Data Integration

In the GIS-based integration procedure, the tolerance of spatial joining was set as 10 meters, which means that a crash location could be marked potentially as far as 10 meters away from the pavement and the roadway. This assumption affects the assignment of crashes to roadway segments and, potentially, the level of accuracy.

8.3.2 Data

The pavement marking retroreflectivity data were collected every five miles, while all other datasets were recorded per mile. As a result, only one of five segments was assigned a pavement marking condition and this caused a lot of missing data in the final dataset.

To resolve the missing data issues, the researchers assumed that the pavement marking condition of road segments within a five-mile segment would be the same. As such, the same values were recorded for segments 2.5 miles forward and 2.5 backward of the available data point.

The crash data included all crashes that occurred on Iowa’s primary roads from 2004 through 2009. It was assumed that all crashes were related either directly or indirectly to asset condition and were considered for further analysis. Hence, the results may overestimate the effect of asset condition on safety.

8.3.3 Estimation of ACI

The thresholds that were used for the operational performance subcomponents (such as IRI, faulting, paint, and so forth) to classify segments into ACI categories from 1 through 3 were based on the literature. The researchers recommend that an expert panel review these thresholds and scores as well.

8.3.4 Statistical Analysis

In this study, all crashes were considered as related only with asset condition. The characteristics of the driver, vehicle, and roadway environment (besides roadway condition) were not taken into account in the statistical analysis.

8.3.5 Economic Analysis

The discount rate throughout the economic analysis was assumed to be four percent. This rate is commonly used for benefit-cost analysis; however, during the analysis period, the banking discount/interest rate was lower (approximately one percent).

Secondly, the researchers applied straight-line depreciation to calculate asset condition depreciation. In fact, the depreciation rate could follow normal, exponential, logarithm, and other distributions, depending on the asset characteristics.

Finally, the study period for the second approach was set as five years. Usually, when alternatives have different service lives, the study period of economic analysis should be the lowest common multiple of the service lives.

In this study, an equivalent annual return analysis was used that may not have taken into account all the costs and benefits throughout the service life of the asset. Therefore, a more comprehensive economic analysis is recommended.

8.4 Recommendations for Future Research

To understand the relationship between asset performance and safety performance better, the following recommendations are offered for future studies.

- *Analysis of future data:* A longer study period for the database developed in this study would help to define the relationship between asset performance and safety performance more accurately. A further process of relating crashes to asset performance measures, based on crash reasons, is expected to improve the accuracy of the research.
- *Replication of this study in other states:* A replication of this study in other states would help verify the results and/or identify differences among states. Similar data resources would be necessary.
- *Consideration of additional asset performance measures:* Only pavement condition and pavement marking performance were included in this study. Additional asset conditions that could be considered in future work include sign inventory, lighting inventory, rumble strip inventory, or guardrail locations.

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APPENDIX A. STATISTICAL ANALYSIS RESULTS

Negative Binomial Model for all data

```
+---------------------------------------------+
| Poisson Regression                          |
| Maximum Likelihood Estimates                |
| Model estimated: Aug 10, 2011 at 01:31:26PM.|
| Dependent variable                 X5       |
| Weighting variable               None       |
| Number of observations          28835       |
| Iterations completed                7       |
| Log likelihood function     -61707.76       |
| Number of parameters                3       |
| Info. Criterion: AIC =        4.28027       |
|   Finite Sample: AIC =        4.28027       |
| Info. Criterion: BIC =        4.28113       |
| Info. Criterion:HQIC =        4.28054       |
| Restricted log likelihood   -80350.34       |
| McFadden Pseudo R-squared    .2320162       |
| Chi squared                  37285.17       |
| Degrees of freedom                  2       |
| Prob[ChiSqd> value] =        .0000000       |
+---------------------------------------------+
| Poisson Regression                          |
| Chi- squared =478954.13437  RsqP=  -.9238   |
| G  - squared = 82779.40960  RsqD=   .3105   |
| Overdispersion tests: g=mu(i)  :  1.349     |
| Overdispersion tests: g=mu(i)^2:   .369     |
+---------------------------------------------+
+--------+--------------+----------------+--------+--------+----------+
|Variable| Coefficient  | Standard Error |b/St.Er.|P[|Z|>z]| Mean of X|
+--------+--------------+----------------+--------+--------+----------+
 Constant|   -5.05857596       .04418893  -114.476   .0000
 X4      |    -.42369909       .01195442   -35.443   .0000   2.24862147
LOGADT   |     .76886336       .00398162   193.103   .0000   8.09345290
+---------------------------------------------+
| Negative Binomial Regression                |
| Maximum Likelihood Estimates                |
| Model estimated: Aug 10, 2011 at 01:31:28PM.|
| Dependent variable                 X5       |
| Weighting variable               None       |
| Number of observations          28835       |
| Iterations completed                9       |
| Log likelihood function     -45714.20       |
| Number of parameters                4       |
| Info. Criterion: AIC =        3.17102       |
```

```
|   Finite Sample: AIC =          3.17102     |
| Info. Criterion: BIC =          3.17217     |
| Info. Criterion:HQIC =          3.17139     |
| Restricted log likelihood     -61707.76     |
| McFadden Pseudo R-squared      .2591822     |
| Chi squared                    31987.11     |
| Degrees of freedom                    1     |
| Prob[ChiSqd> value] =          .0000000     |
| NegBin form 2; Psi(i) = theta               |
+---------------------------------------------+
+--------+--------------+----------------+--------+--------+----------+
|Variable| Coefficient  | Standard Error |b/St.Er.|P[|Z|>z]| Mean of X|
+--------+--------------+----------------+--------+--------+----------+
 Constant|   -5.38145833       .03959308  -135.919   .0000
 X4      |   -1.29146309       .01743908   -16.713   .0000   2.24862147
LOGADT   |     .77074842       .00340283   226.502   .0000   8.09345290
---------+Dispersion parameter for count data model
 Alpha   |    1.26899021       .01547431    82.006   .0000
```

Model for ACI≤1.5

```
+---------------------------------------------+
| Poisson Regression                          |
| Maximum Likelihood Estimates                |
| Model estimated: Aug 10, 2011 at 01:43:00PM.|
| Dependent variable                   X5     |
| Weighting variable                 None     |
| Number of observations              906     |
| Iterations completed                  7     |
| Log likelihood function       -3998.108     |
| Number of parameters                  3     |
| Info. Criterion: AIC =          8.83247     |
|   Finite Sample: AIC =          8.83250     |
| Info. Criterion: BIC =          8.84839     |
| Info. Criterion:HQIC =          8.83855     |
| Restricted log likelihood     -5067.105     |
| McFadden Pseudo R-squared      .2109680     |
| Chi squared                    2137.994     |
| Degrees of freedom                    2     |
| Prob[ChiSqd> value] =          .0000000     |
+---------------------------------------------+
| Poisson Regression                          |
| Chi- squared =111502.72930  RsqP= -6.5568   |
| G  - squared =  6314.96551  RsqD=   .2529   |
| Overdispersion tests: g=mu(i)  :  1.068     |
| Overdispersion tests: g=mu(i)^2:   .086     |
+---------------------------------------------+
```

```
+--------+--------------+----------------+--------+--------+----------+
|Variable| Coefficient  | Standard Error |b/St.Er.|P[|Z|>z]| Mean of X|
+--------+--------------+----------------+--------+--------+----------+
 Constant|   -2.04571310       .17372009   -11.776   .0000
 X4      |   -1.84200974       .08895010   -20.708   .0000   1.36843267
LOGADT   |     .66361644       .01578168    42.050   .0000   8.45094362
+---------------------------------------------+
| Negative Binomial Regression                |
| Maximum Likelihood Estimates                |
| Model estimated: Aug 10, 2011 at 01:43:00PM.|
| Dependent variable                 X5       |
| Weighting variable               None       |
| Number of observations            906       |
| Iterations completed               10       |
| Log likelihood function       -1999.835     |
| Number of parameters                4       |
| Info. Criterion: AIC =          4.42348     |
|   Finite Sample: AIC =          4.42353     |
| Info. Criterion: BIC =          4.44471     |
| Info. Criterion:HQIC =          4.43158     |
| Restricted log likelihood     -3998.108     |
| McFadden Pseudo R-squared      .4998047     |
| Chi squared                    3996.547     |
| Degrees of freedom                    1     |
| Prob[ChiSqd> value] =          .0000000     |
| NegBin form 2; Psi(i) = theta               |
+---------------------------------------------+
+--------+--------------+----------------+--------+--------+----------+
|Variable| Coefficient  | Standard Error |b/St.Er.|P[|Z|>z]| Mean of X|
+--------+--------------+----------------+--------+--------+----------+
 Constant|     .77990616       .54169051     1.440   .1499
 X4      |   -1.66786220       .41533061    -4.016   .0001   1.36843267
 LOGADT  |     .31620081       .00994591    31.792   .0000   8.45094362
---------+Dispersion parameter for count data model
 Alpha   |    2.47848458       .15028148    16.492   .0000
```

Model for ACI>1.5

```
+---------------------------------------------+
| Poisson Regression                          |
| Maximum Likelihood Estimates                |
| Model estimated: Aug 10, 2011 at 02:24:01PM.|
| Dependent variable                  X5      |
| Weighting variable                None      |
| Number of observations           27929      |
| Iterations completed                 7      |
| Log likelihood function      -57508.09      |
| Number of parameters                 3      |
| Info. Criterion: AIC =         4.11838      |
|   Finite Sample: AIC =         4.11838      |
| Info. Criterion: BIC =         4.11926      |
| Info. Criterion:HQIC =         4.11866      |
| Restricted log likelihood    -74344.40      |
| McFadden Pseudo R-squared     .2264637      |
| Chi squared                   33672.61      |
| Degrees of freedom                   2      |
| Prob[ChiSqd> value] =         .0000000      |
+---------------------------------------------+
| Poisson Regression                          |
| Chi- squared =137081.60890  RsqP=   .3834   |
| G  - squared = 76061.33369  RsqD=   .3069   |
| Overdispersion tests: g=mu(i)  : 10.218     |
| Overdispersion tests: g=mu(i)^2: 10.194     |
+---------------------------------------------+
```

Variable	Coefficient	Standard Error	b/St.Er.	P[abs(Z)>z]	Mean of X
Constant	-5.33495527	.04796242	-111.232	.0000	
X4	-.31971309	.01486877	-21.502	.0000	2.27717426
LOGADT	.77262977	.00414876	186.232	.0000	8.08185612

```
+---------------------------------------------+
| Negative Binomial Regression                |
| Maximum Likelihood Estimates                |
| Model estimated: Aug 10, 2011 at 02:24:04PM.|
| Dependent variable                  X5      |
| Weighting variable                None      |
| Number of observations           27929      |
| Iterations completed                10      |
| Log likelihood function      -43570.57      |
| Number of parameters                 4      |
| Info. Criterion: AIC =         3.12038      |
|   Finite Sample: AIC =         3.12038      |
| Info. Criterion: BIC =         3.12156      |
```

```
| Info. Criterion:HQIC =          3.12076     |
| Restricted log likelihood     -57508.09     |
| McFadden Pseudo R-squared      .2423576     |
| Chi squared                   27875.04     |
| Degrees of freedom                  1     |
| Prob[ChiSqd> value] =         .0000000     |
| NegBin form 2; Psi(i) = theta              |
+--------------------------------------------+
+---------+--------------+----------------+--------+---------+----------+
|Variable| Coefficient  | Standard Error |b/St.Er.|P[|Z|>z]| Mean of X|
+---------+--------------+----------------+--------+---------+----------+
 Constant|   -5.76123896       .07247317   -79.495   .0000
 X4      |    -.17940674       .02269576    -7.905   .0000   2.27717426
 LOGADT  |     .78434830       .00568427   137.986   .0000   8.08185612
---------+Dispersion parameter for count data model
 Alpha   |    1.22333346       .01529867    79.963   .0000
```

APPENDIX B. ECONOMIC ANALYSIS

Table B.1. Reduced number of crashes by severity

	Crashes					
Alternatives	**Reduced Crash**	**Fatal (K)**	**Disabling Injury (A)**	**Evident Injury (B)**	**Possible Injury (C)**	**PDO (O)**
Reconstruction	1.520	0.0182	0.0578	0.1474	0.3435	0.9515
Major	1.515	0.0182	0.0576	0.1470	0.3424	0.9484
Minor	1.487	0.0178	0.0565	0.1442	0.3361	0.9309
Paint	0.040	0.0005	0.0015	0.0039	0.0090	0.0250
Durable	0.151	0.0018	0.0057	0.0146	0.0341	0.0945
Tape	0.202	0.0024	0.0077	0.0196	0.0457	0.1265

Table B.2. Benefit from reduced numbers of crashes

	Benefit						
Alternatives	**Fatal (K)**	**Disabling Injury (A)**	**Evident Injury (B)**	**Possible Injury (C)**	**PDO (O)**	**Benefit (2007)**	**Benefit (2011)**
Reconstruction	$63,840.00	$13,862.40	$7,077.12	$8,588.00	$2,569.10	95,936.62	$112,232.28
Major	$63,630.00	$13,816.80	$7,053.84	$8,559.75	$2,560.65	$95,621.04	$111,863.10
Minor	$62,454.00	$13,561.44	$6,923.47	$8,401.55	$2,513.33	$93,853.79	$109,795.66
Paint	$1,680.00	$364.80	$186.24	$226.00	$67.61	$2,524.65	$2,953.48
Durable	$6,342.00	$1,377.12	$703.06	$853.15	$255.22	$9,530.55	$11,149.39
Tape	$8,484.00	$1,842.24	$940.51	$1,141.30	$341.42	$12,749.47	$14,915.08

Five-Year Net Present Value (NPV) Analysis

Range 1: 1.5<ACI

Table B.3. Reconstruction NPV in Range 1

Reconstruction						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0.0000	0.0000	0	0.00	73581.75	-73581.75
1	2.8649	0.0984	2.7665	204270.13	73581.75	125661.91
2	3.2467	0.1076	3.1391	231781.81	73581.75	146264.85
3	3.6793	0.1175	3.5618	262992.72	73581.75	168385.66
4	4.1696	0.1284	4.0412	298390.19	73581.75	192167.20
5	4.7252	0.1402	4.585	338542.77	73581.75	217778.64
					NPV	776676.51

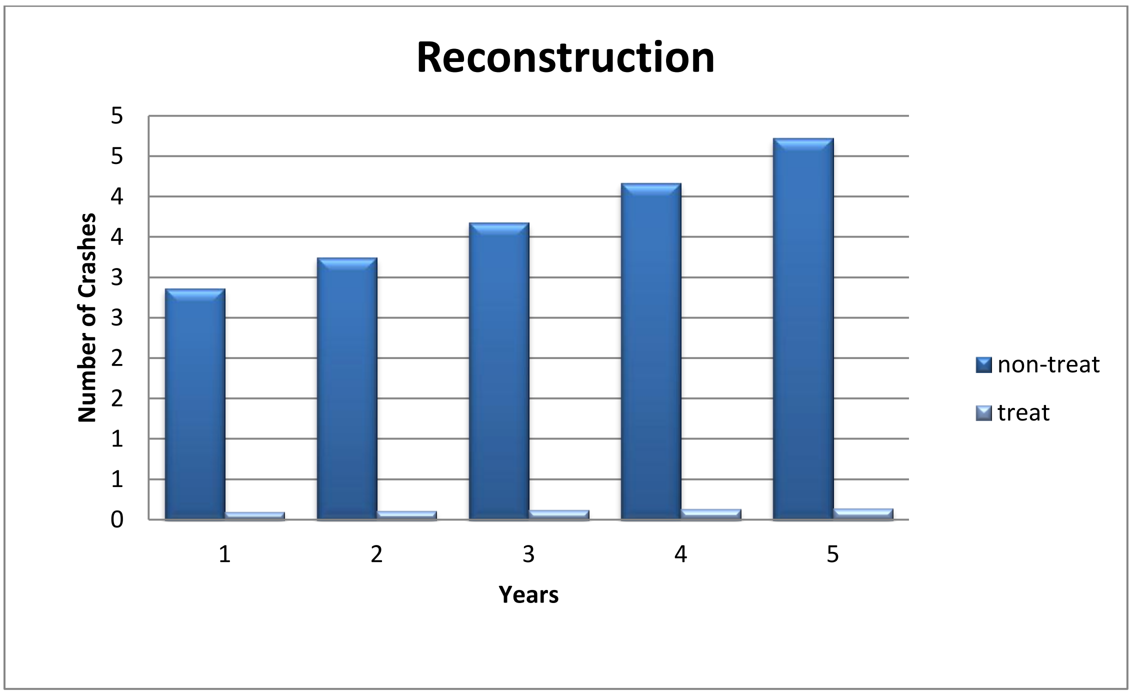

Figure B.1. Reconstruction NPV in Range 1

Table B.4. Major rehabilitation NPV in Range 1

Major						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	61645.47	-61645.47
1	2.8649	0.1871	2.6778	197720.79	61645.47	130841.65
2	3.6793	0.2233	3.456	255180.76	61645.47	178934.26
3	4.6992	0.2665	4.4327	327297.39	61645.47	236163.59
4	6.0944	0.3181	5.7763	426504.82	61645.47	311883.30
5	6.0944	0.3797	5.7147	421956.46	61645.47	296149.37
					NPV	1092326.69

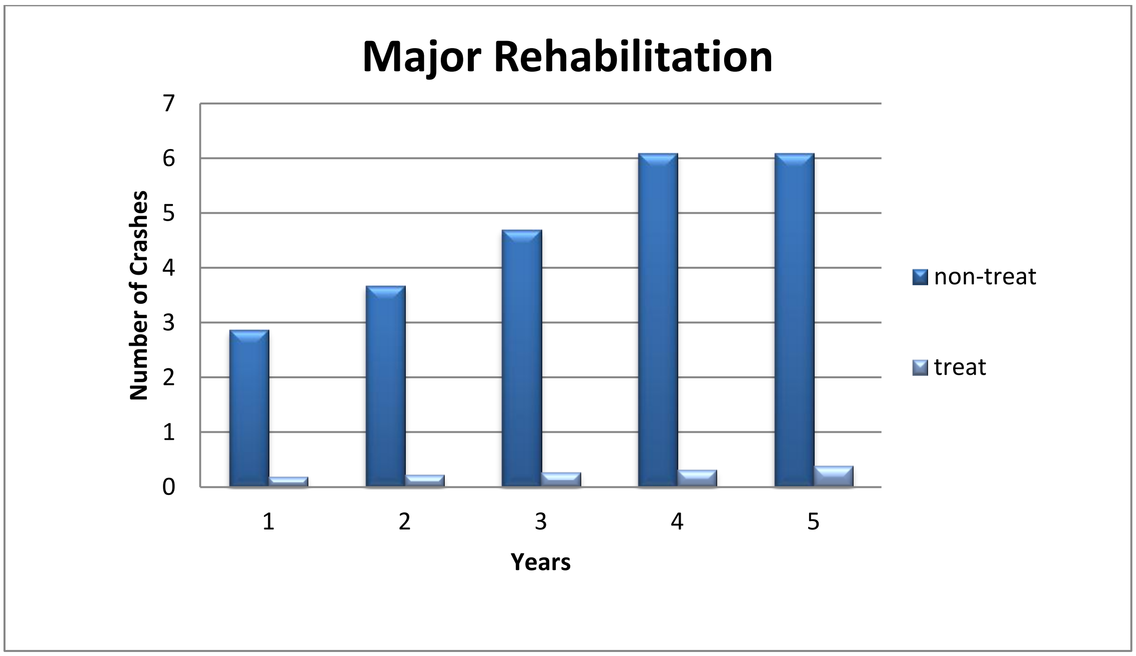

Figure B.2. Major rehabilitation NPV in Range 1

Table B.5. Minor rehabilitation NPV in Range 1

Minor						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	54052.28	-54052.28
1	2.8649	0.3374	2.5275	186623.09	54052.28	127471.93
2	6.0944	1.595	4.4994	332222.32	54052.28	257183.84
3	6.0944	5.5871	0.5073	37457.52	54052.28	-14752.68
4	6.0944	0.4715	5.6229	415178.22	54052.28	308691.96
5	6.0944	5.5871	0.5073	37457.52	54052.28	-13639.68
					NPV	610903.09

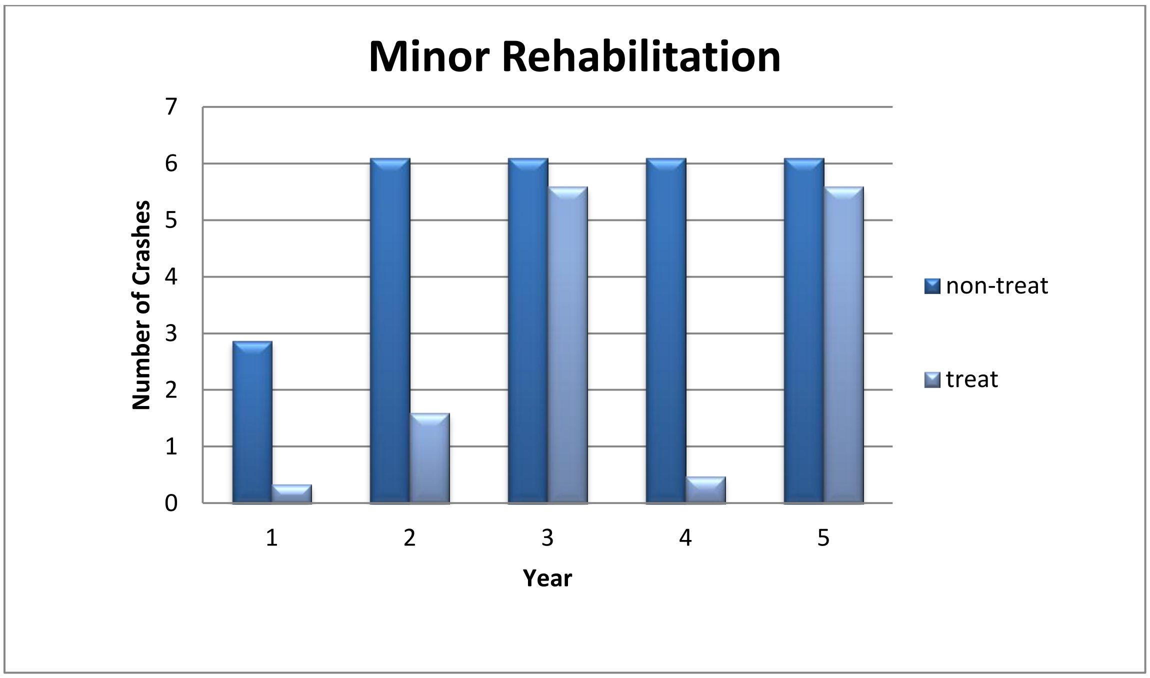

Figure B.3. Minor rehabilitation NPV in Range 1

Table B.6. Paint marking NPV in Range 1

Paint						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	2376.00	-2376.00
1	2.8649	1.5704	1.2945	95582.03	2376.00	89621.18
2	6.0944	5.9936	0.1008	7442.77	2376.00	4684.52
3	6.0944	5.9936	0.1008	7442.77	2376.00	4504.34
4	6.0944	5.9936	0.1008	7442.77	2376.00	4331.10
5	6.0944	5.9936	0.1008	7442.77	2376.00	4164.52
					NPV	104929.66

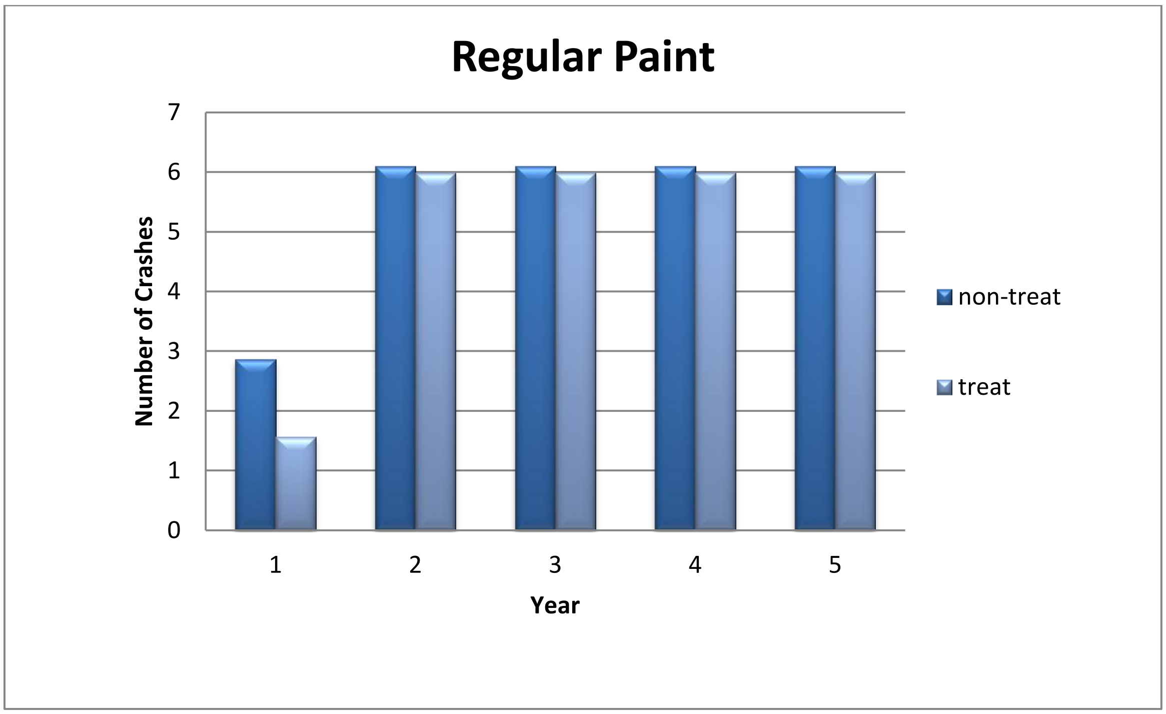

Figure B.4. Paint marking NPV in Range 1

Table B.7. Durable marking NPV in Range 1

Durable						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	6298.73	-6298.73
1	2.8649	1.1898	1.6751	123684.40	6298.73	112870.84
2	6.0944	5.8344	0.26	19197.63	6298.73	11925.76
3	6.0944	5.3676	0.7268	53664.75	6298.73	42108.22
4	6.0944	5.8344	0.26	19197.63	6298.73	11026.03
5	6.0944	5.3676	0.7268	53664.75	6298.73	38931.42
					NPV	210563.54

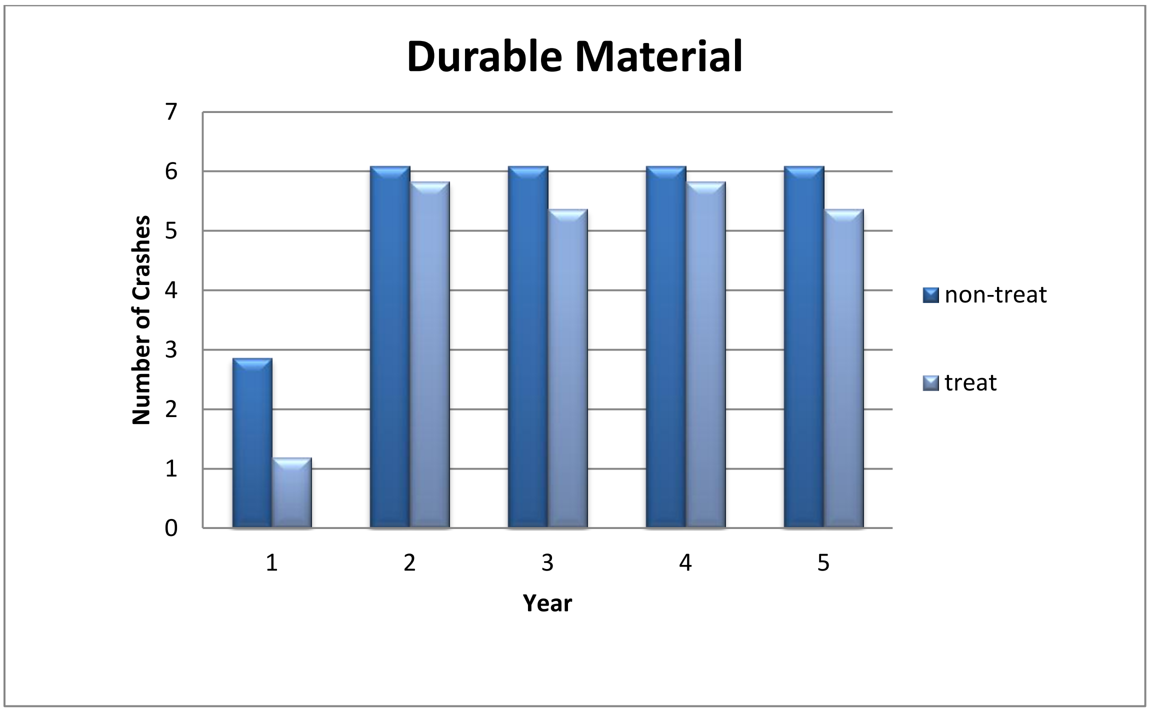

Figure B.5. Durable marking NPV in Range 1

Table B.8. Tape marking NPV in Range 1

Tape						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	10674.28	-10674.28
1	2.8649	0.5118	2.3531	173745.91	10674.28	156799.64
2	4.6992	3.3849	1.3143	97044.00	10674.28	79853.66
3	6.0944	5.4578	0.6366	47004.65	10674.28	32297.57
4	6.0944	6.0944	0	0.00	10674.28	-9124.42
5	6.0944	6.0944	0	0.00	10674.28	-8773.48
					NPV	240378.69

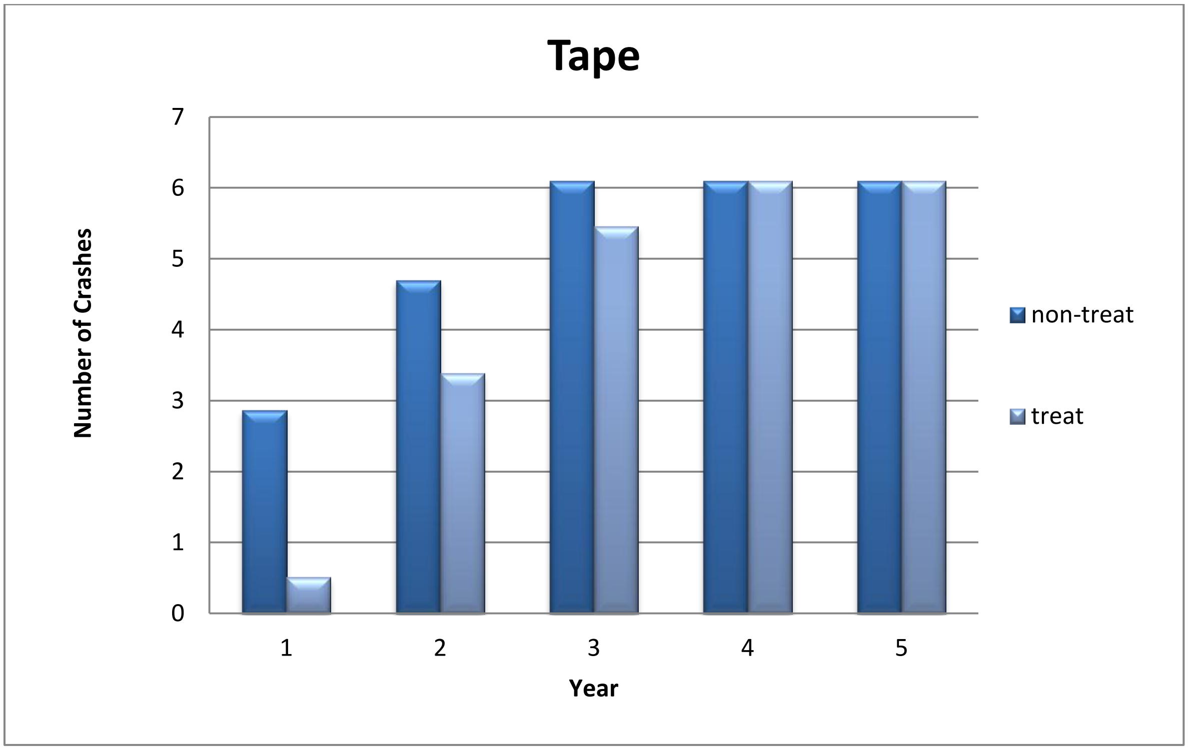

Figure B.6. Tape marking NPV in Range 1

Range 2: 1.5<ACI≤2.0

Table B.9. Reconstruction NPV in Range 2

Reconstruction						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	73581.75	-73581.75
1	0.2409	0.0612	0.1797	13268.51	73581.75	-57993.50
2	0.359	0.0669	0.2921	21567.80	73581.75	-48089.83
3	0.4629	0.0731	0.3898	28781.67	73581.75	-39827.11
4	0.8216	0.0798	0.7418	54772.31	73581.75	-16078.39
5	0.988	0.0872	0.9008	66512.39	73581.75	-5810.50
					NPV	-241381.06

Figure B.7. Reconstruction NPV in Range 2

Table B.10. Major rehabilitation NPV in Range 2

Major						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	61645.47	-61645.47
1	0.2409	0.0741	0.1668	12316.02	61645.47	-47432.17
2	0.4629	0.0884	0.3745	27651.97	61645.47	-31428.91
3	0.988	0.1055	0.8825	65161.18	61645.47	3125.45
4	2.011	0.1259	1.8851	139190.18	61645.47	66285.54
5	3.5365	0.1503	3.3862	250026.94	61645.47	154835.84
					NPV	83740.28

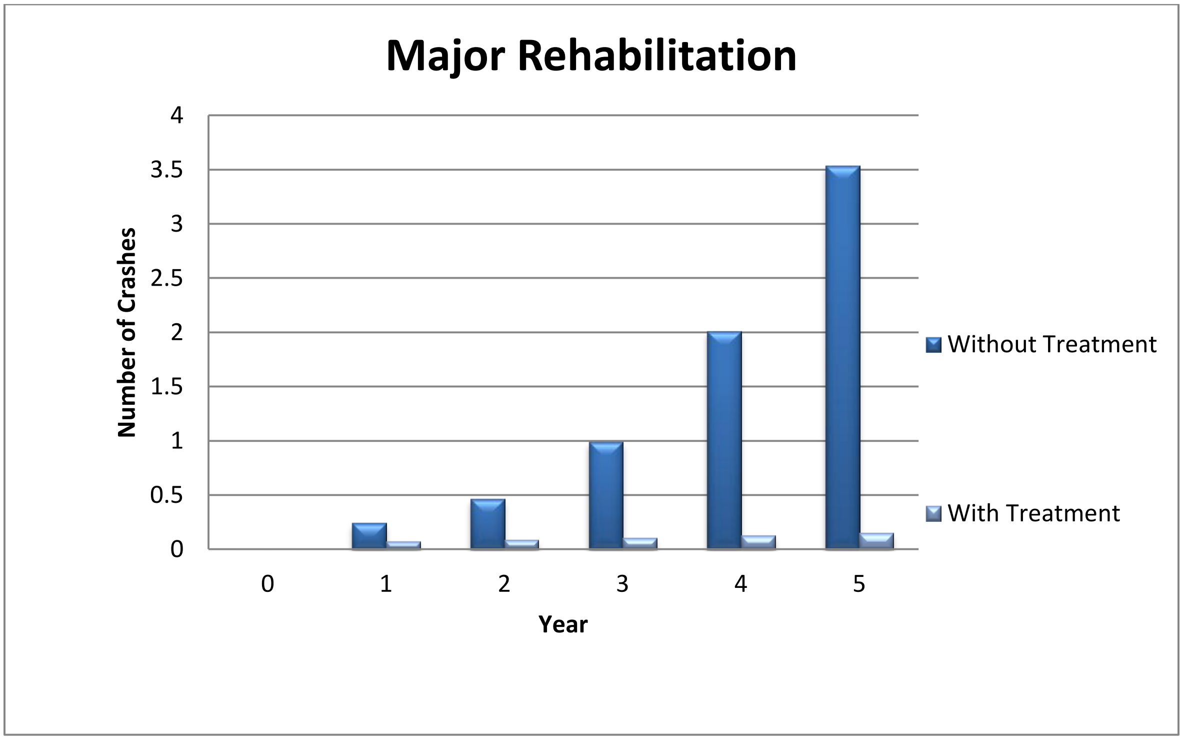

Figure B.8. Major rehabilitation NPV in Range 2

Table B.11. Minor rehabilitation NPV in Range 2

Minor						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	54052.28	-54052.28
1	0.2409	0.1336	0.1073	7922.71	54052.28	-44355.35
2	2.468	0.2409	2.2271	164442.44	54052.28	102061.91
3	5.258	2.468	2.79	206005.30	54052.28	135085.69
4	5.258	0.2404	5.0176	370484.67	54052.28	270487.73
5	5.258	2.468	2.79	206005.30	54052.28	124894.31
					NPV	534122.00

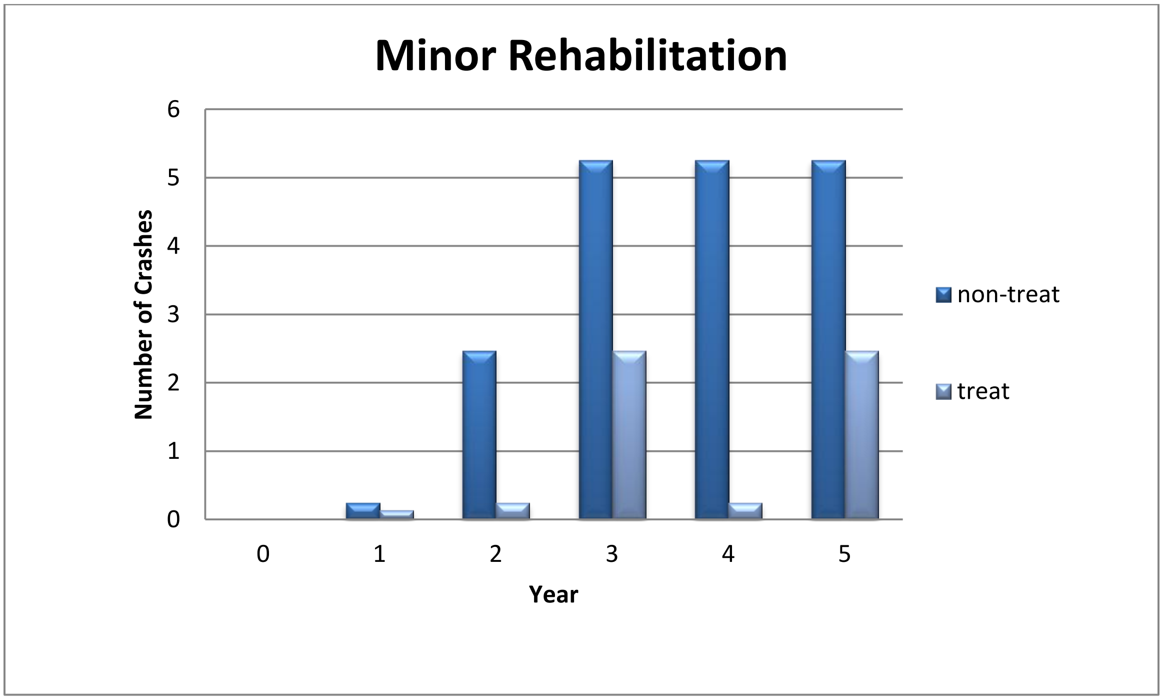

Figure B.9 Minor rehabilitation NPV in Range 2

Table B.12. Paint marking NPV in Range 2

Paint						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	2376.00	-2376.00
1	0.249	0.2381	0.0109	804.82	2376.00	-1510.75
2	5.258	5.171	0.087	6423.82	2376.00	3742.44
3	5.258	5.171	0.087	6423.82	2376.00	3598.50
4	5.258	5.171	0.087	6423.82	2376.00	3460.09
5	5.258	5.171	0.087	6423.82	2376.00	3327.01
					NPV	10241.30

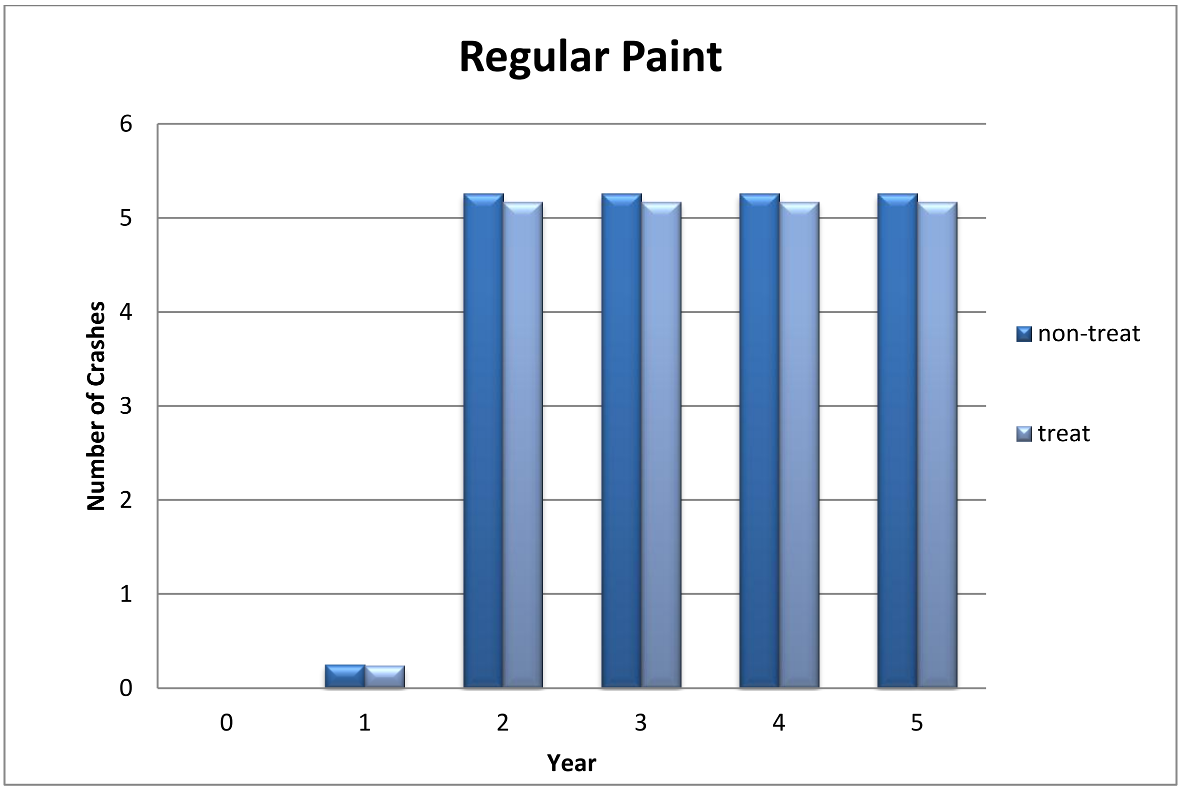

Figure B.10. Paint marking NPV in Range 2

Table B.13. Durable marking NPV in Range 2

Durable						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	6298.73	-6298.73
1	0.2409	0.2271	0.0138	1018.95	6298.73	-5076.71
2	4.2875	4.0397	0.2478	18296.82	6298.73	11092.90
3	5.258	3.7165	1.5415	113819.78	6298.73	95585.82
4	5.258	5.258	0	0.00	6298.73	-5384.18
5	5.258	4.8373	0.4207	31063.24	6298.73	20354.62
					NPV	110273.72

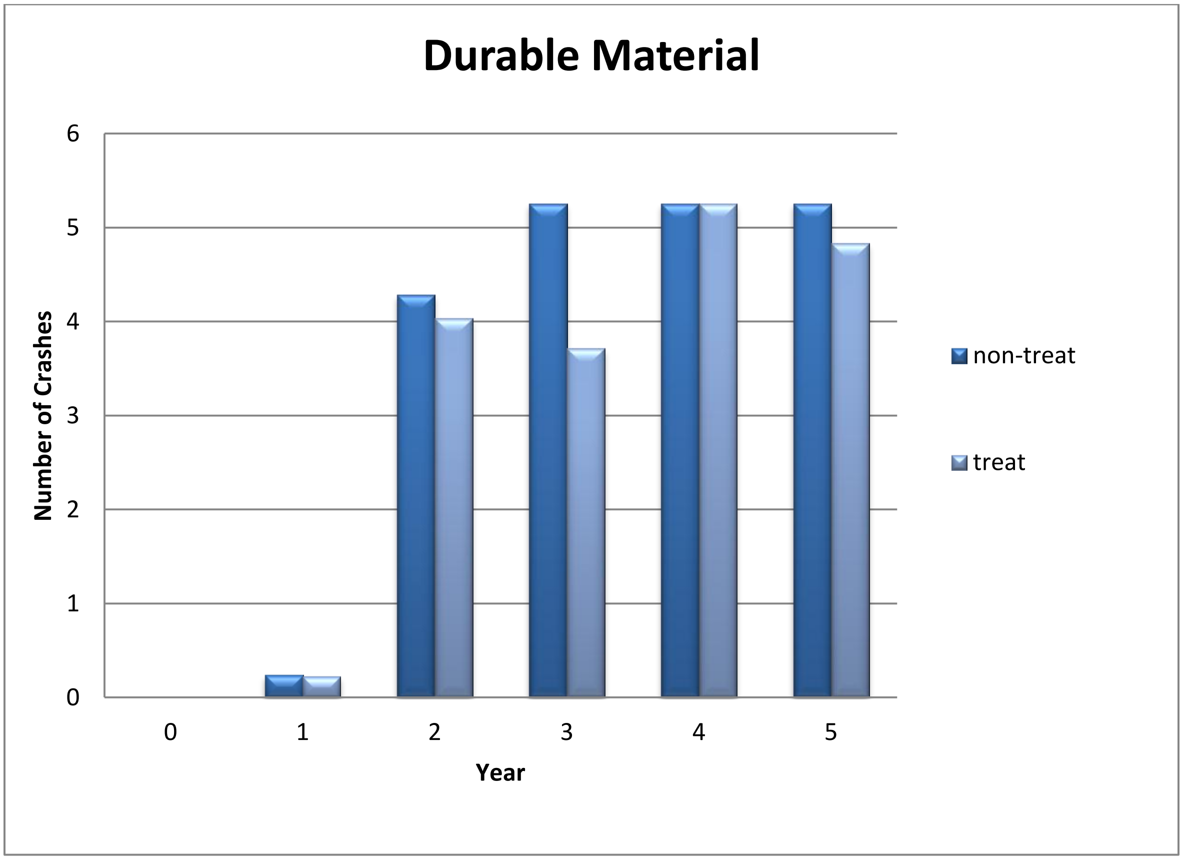

Figure B.11. Durable marking NPV in Range 2

Table B.14. Tape marking NPV in Range 2

Tape						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	10674.28	-10674.28
1	0.2409	0.1903	0.0506	3736.15	10674.28	-6671.28
2	0.988	0.3712	0.6168	45542.68	10674.28	32237.79
3	3.5142	1.567	1.9472	143775.46	10674.28	118326.46
4	4.9808	4.0397	0.9411	69488.03	10674.28	50274.24
5	5.258	5.258	0	0.00	10674.28	-8773.48
					NPV	174719.46

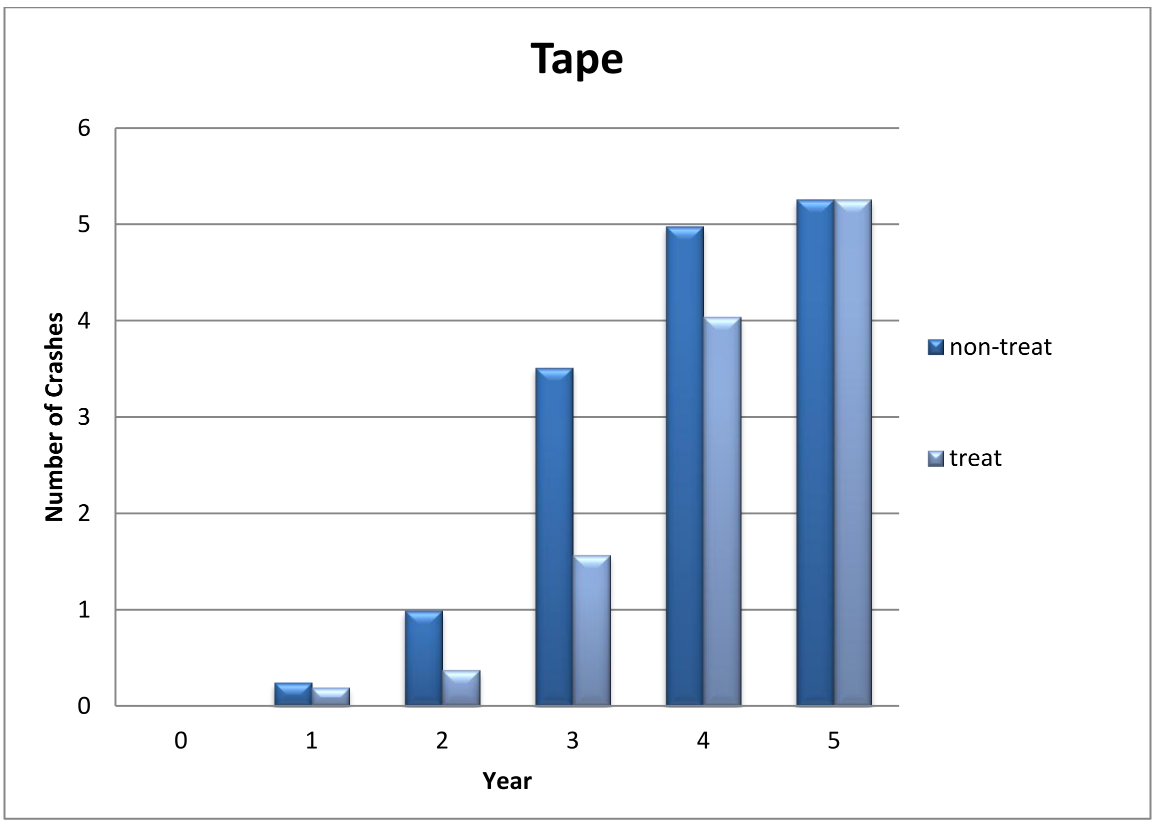

Figure B.12. Tape marking NPV in Range 2

Range 3: 2.0≤ACI<2.25

Table B.15. Reconstruction NPV in Range 3

Reconstruction						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	73581.75	-73581.75
1	0.1918	0.0708	0.121	8934.28	73581.75	-62161.03
2	0.2096	0.0773	0.1323	9768.64	73581.75	-58998.81
3	0.2289	0.0845	0.1444	10662.07	73581.75	-55935.37
4	0.2501	0.0923	0.1578	11651.48	73581.75	-52938.25
5	0.2733	0.1008	0.1725	12736.89	73581.75	-50010.04
					NPV	-353625.25

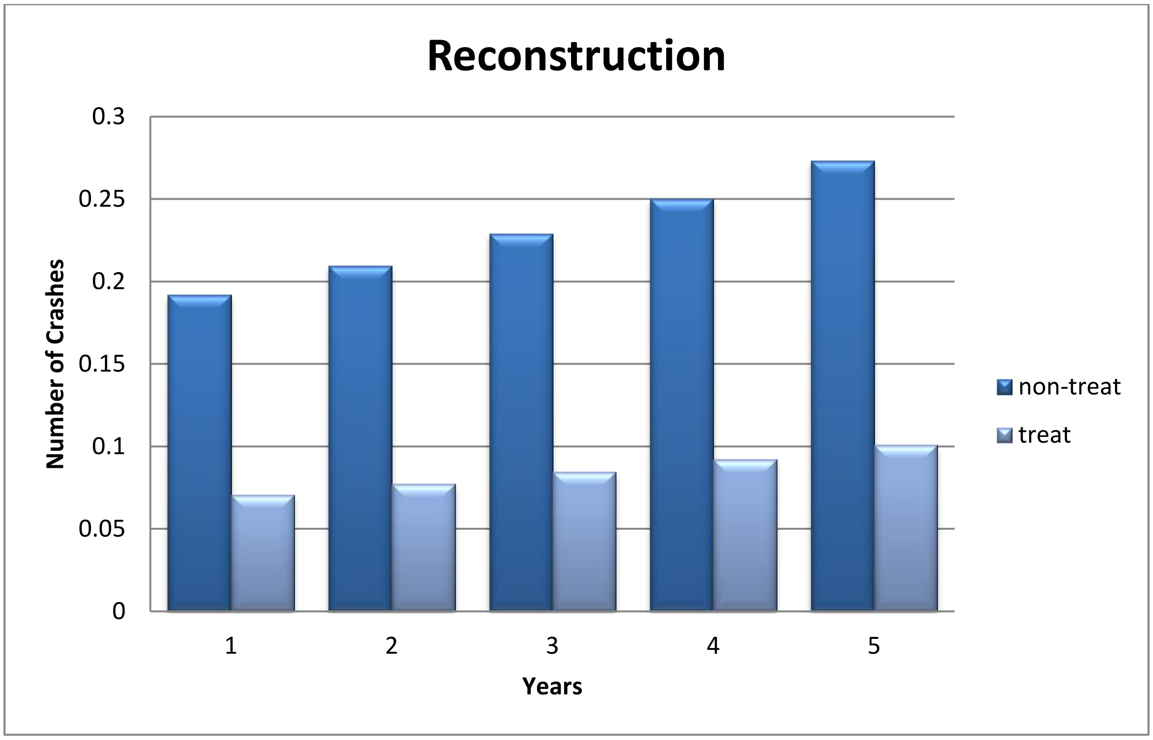

Figure B.13. Reconstruction NPV in Range 3

Table B.16. Major rehabilitation NPV in Range 3

Major						
year	non-treat	treat	reduce	Benefit	Cost (EUAC)	PV
0	0	0	0	0.00	61645.47	-61645.47
1	0.1918	0.0708	0.121	8934.28	61645.47	-50683.84
2	0.2289	0.0773	0.1516	11193.69	61645.47	-46645.51
3	0.2733	0.0845	0.1888	13940.43	61645.47	-42409.61
4	0.3261	0.0923	0.2338	17263.10	61645.47	-37938.24
5	0.8058	0.1008	0.705	52055.10	61645.47	-7882.58
					NPV	-247205.25

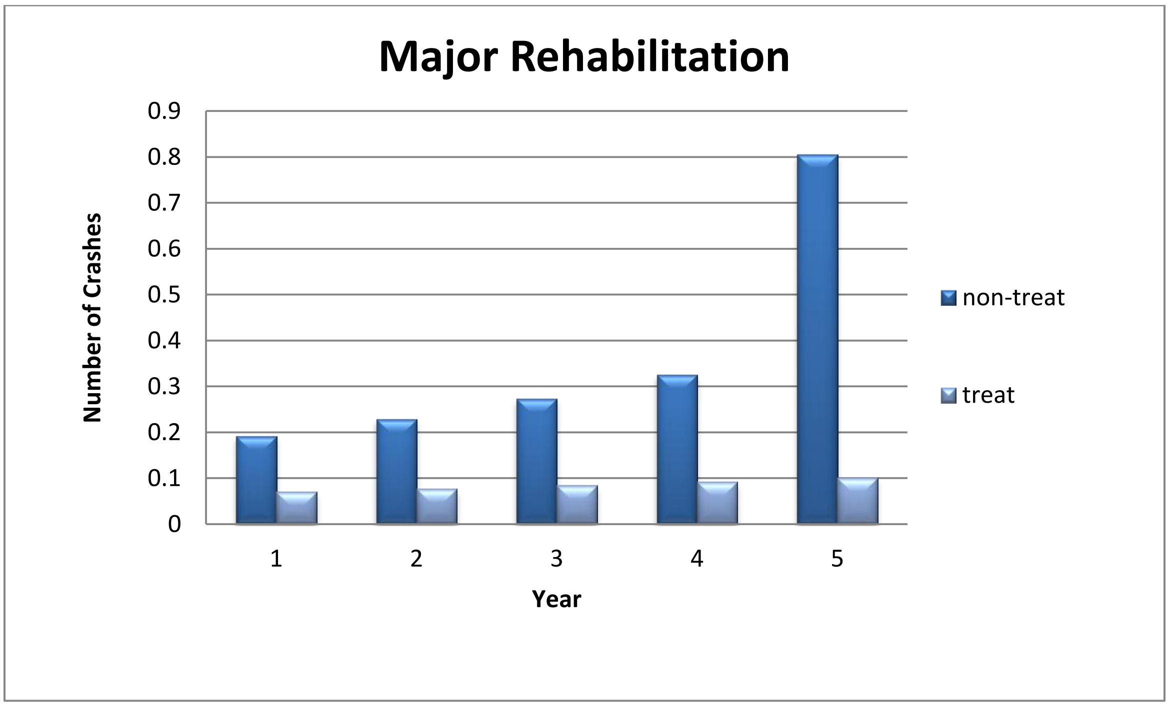

Figure B.14. Major rehabilitation NPV in Range 3

Table B.17. Minor rehabilitation NPV in Range 3

Minor						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	54052.28	-54052.28
1	0.1918	0.1064	0.0854	6305.68	54052.28	-45910.19
2	0.3459	0.1918	0.1541	11378.29	54052.28	-39454.51
3	4.2821	0.3459	3.9362	290637.31	54052.28	210323.23
4	5.5141	4.2821	1.232	90967.22	54052.28	31555.04
5	5.5141	5.5141	0	0.00	54052.28	-44427.03
					NPV	58034.25

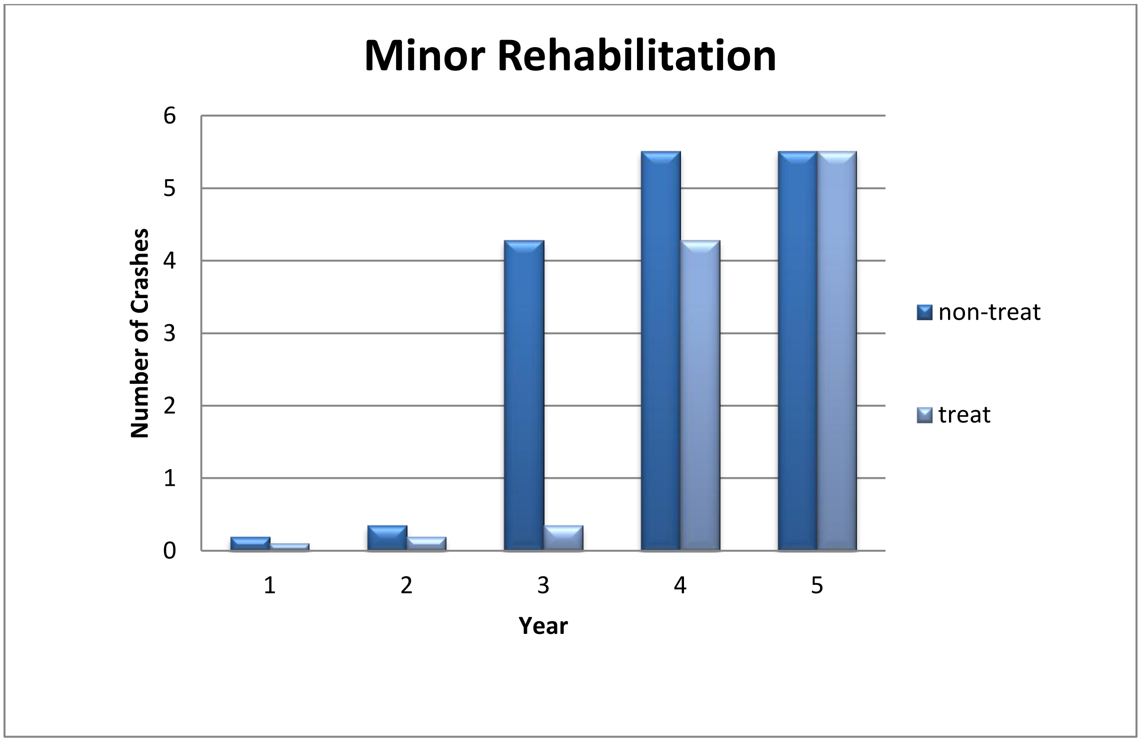

Figure B.15. Minor rehabilitation NPV in Range 3

Table B.18. Paint marking NPV in Range 3

Paint						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	2376.00	-2376.00
1	0.1918	0.1896	0.0022	162.44	2376.00	-2128.42
2	5.5141	5.4229	0.0912	6733.94	2376.00	4029.16
3	5.5141	5.4229	0.0912	6733.94	2376.00	3874.19
4	5.5141	5.4229	0.0912	6733.94	2376.00	3725.18
5	5.5141	5.4229	0.0912	6733.94	2376.00	3581.91
					NPV	10706.02

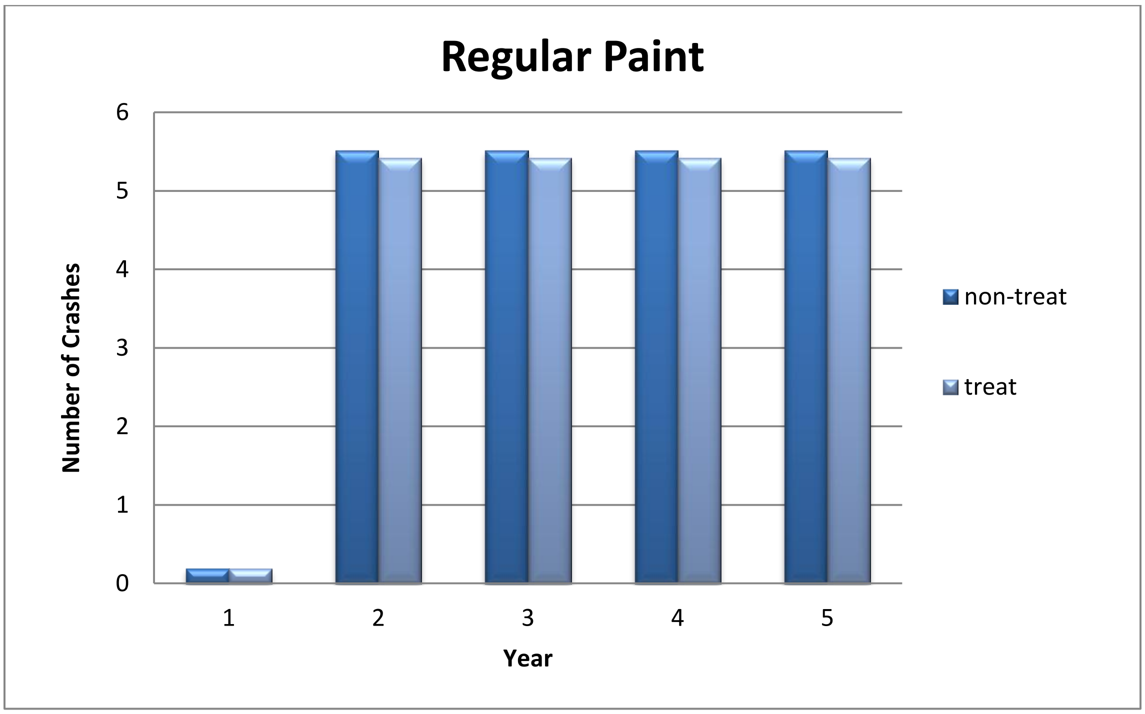

Figure B.16. Paint marking NPV in Range 3

Table B.19. Durable marking NPV in Range 3

Durable						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	6298.73	-6298.73
1	0.1918	0.1808	0.011	812.21	6298.73	-5275.50
2	2.3611	1.8584	0.5027	37117.87	6298.73	28494.03
3	5.5141	1.1559	4.3582	321796.53	6298.73	280476.40
4	5.5141	5.5141	0	0.00	6298.73	-5384.18
5	5.5141	5.0729	0.4412	32576.90	6298.73	21598.74
					NPV	313610.75

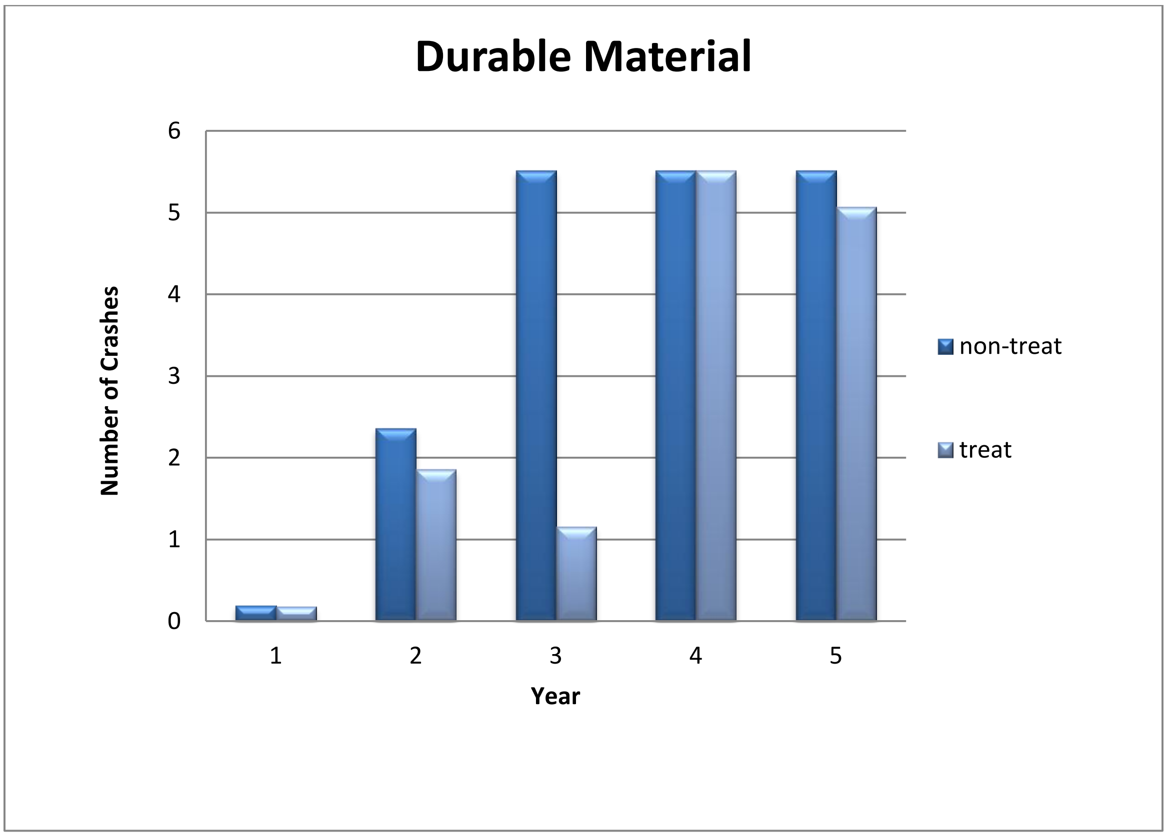

Figure B.17. Durable marking NPV in Range 3

Table B.20. Tape marking NPV in Range 1

Tape						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	10674.28	-10674.28
1	0.1918	0.1515	0.0403	2975.63	10674.28	-7402.55
2	0.2733	0.2158	0.0575	4245.63	10674.28	-5943.65
3	0.8058	0.3075	0.4983	36792.99	10674.28	23219.44
4	3.6242	1.8584	1.7658	130381.42	10674.28	102326.17
5	5.4087	4.2821	1.1266	83184.79	10674.28	59598.36
					NPV	161123.49

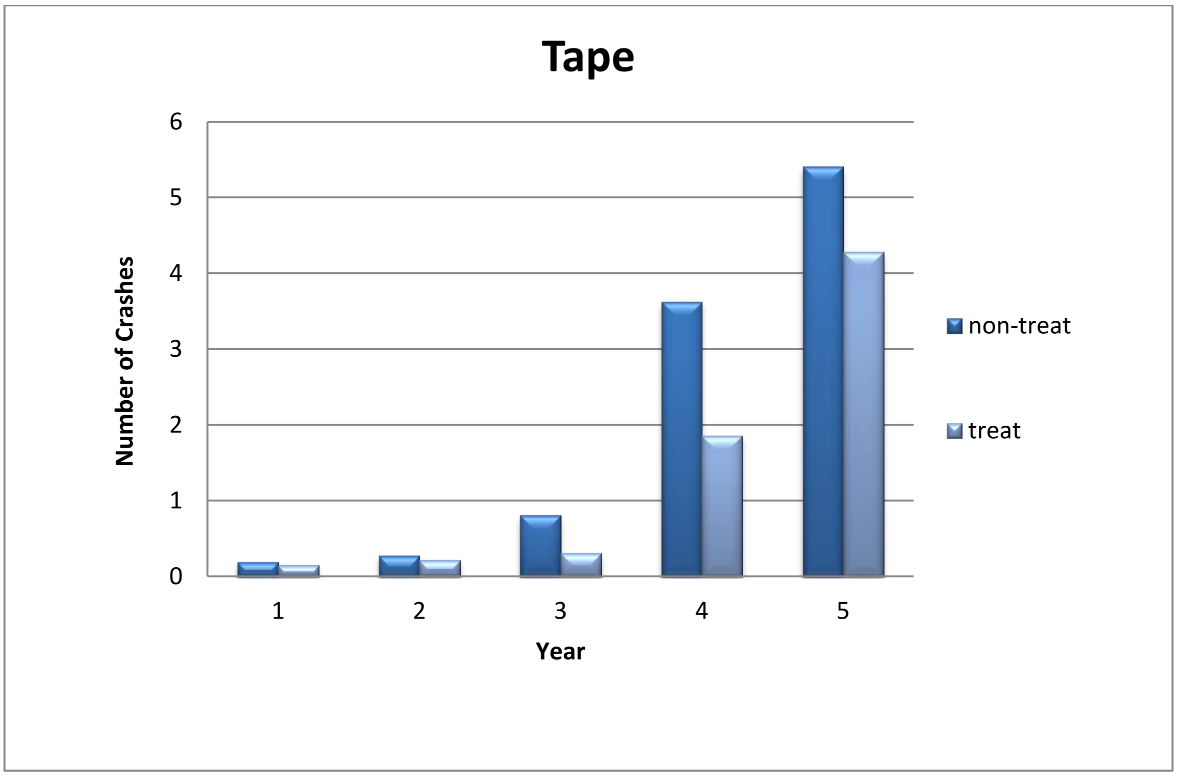

Figure B.18. Tape marking NPV in Range 1

Range 4: 2.25<ACI≤2.50

Table B.21. Reconstruction NPV in Range 4

Reconstruction						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	73581.75	-73581.75
1	0.1569	0.0778	0.0791	5840.51	73581.75	-65135.81
2	0.1714	0.085	0.0864	6379.52	73581.75	-62132.24
3	0.1873	0.0929	0.0944	6970.22	73581.75	-59217.41
4	0.2046	0.1015	0.1031	7612.60	73581.75	-56390.71
5	0.2235	0.1109	0.1126	8314.05	73581.75	-53645.29
					NPV	-370103.21

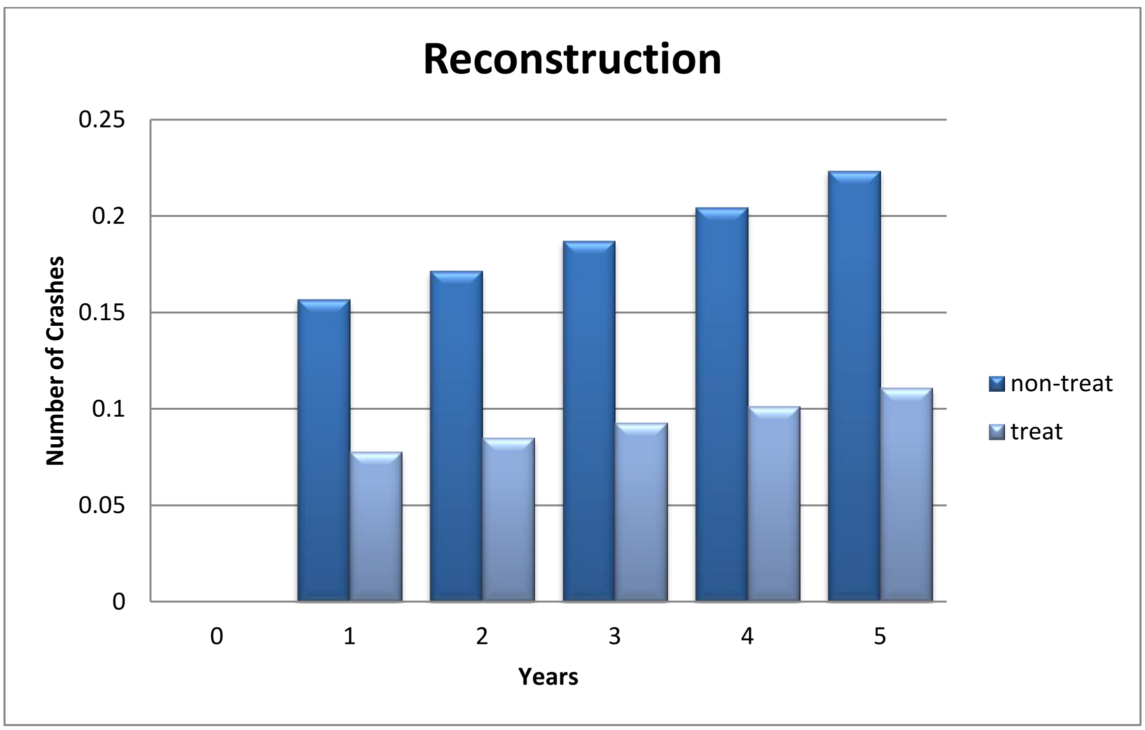

Figure B.19. Reconstruction NPV in Range 4

Table B.22. Major rehabilitation NPV in Range 4

Major						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	61645.47	-61645.47
1	0.1569	0.0778	0.0791	5840.51	61645.47	-53658.62
2	0.1873	0.0929	0.0944	6970.22	61645.47	-50550.35
3	0.2235	0.1109	0.1126	8314.05	61645.47	-47411.44
4	0.2668	0.1323	0.1345	9931.08	61645.47	-44205.68
5	0.3184	0.1579	0.1605	11850.84	61645.47	-40927.56
					NPV	-298399.11

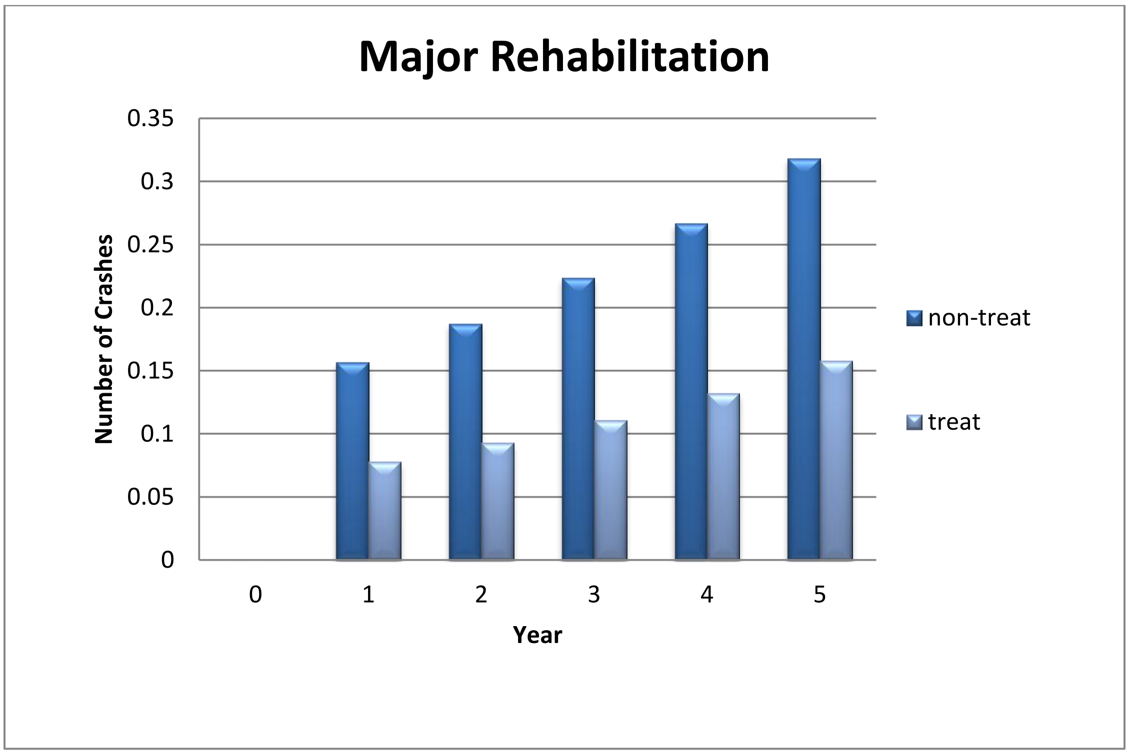

Figure B.20. Major rehabilitation NPV in Range 4

Table B.23. Minor rehabilitation NPV in Range 4

Minor						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	54052.28	-54052.28
1	0.1569	0.087	0.0699	5161.21	54052.28	-47010.65
2	0.283	0.1569	0.1261	9310.85	54052.28	-41365.97
3	2.3949	0.283	2.1119	155936.42	54052.28	90574.63
4	5.6707	0.1569	5.5138	407122.60	54052.28	301805.99
5	5.6707	0.283	5.3877	397811.75	54052.28	282545.23
					NPV	532496.94

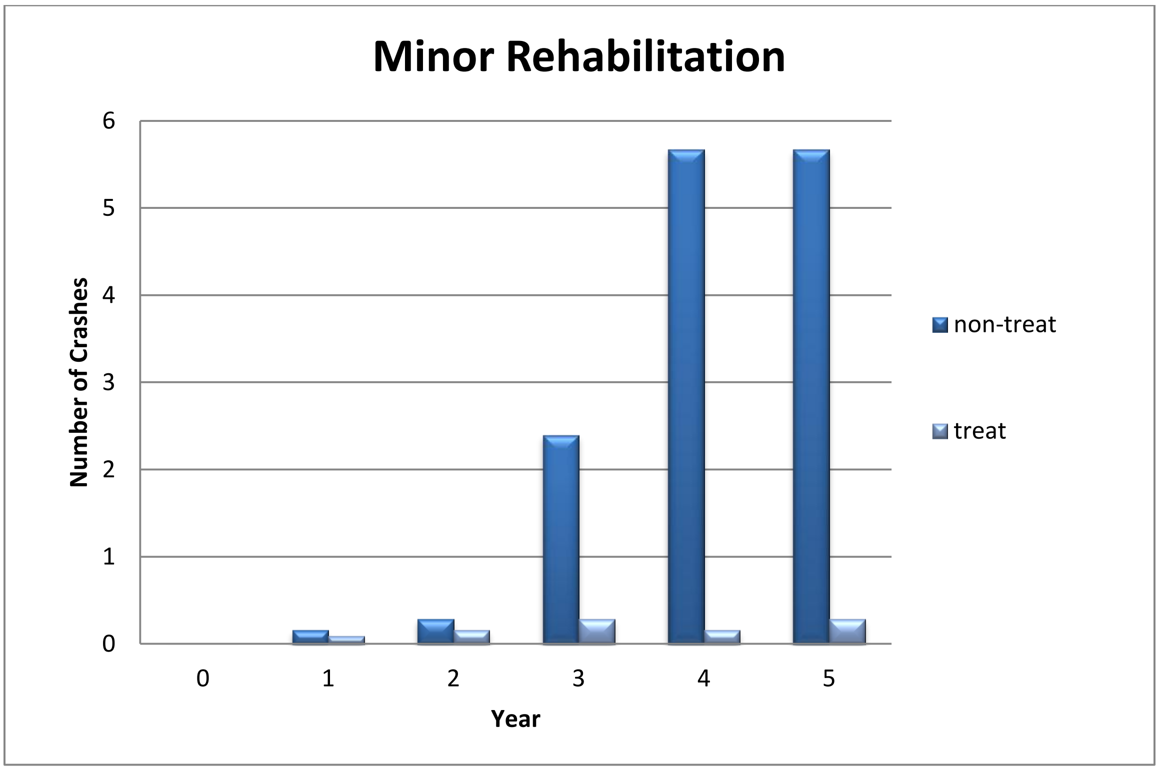

Figure B.21. Minor rehabilitation NPV in Range 4

Table B.24. Paint marking NPV in Range 4

Paint						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	2376.00	-2376.00
1	0.1569	0.1551	0.0018	132.91	2376.00	-2156.82
2	5.6707	5.5769	0.0938	6925.91	2376.00	4206.65
3	5.6707	5.5769	0.0938	6925.91	2376.00	4044.86
4	5.6707	5.5769	0.0938	6925.91	2376.00	3889.28
5	5.6707	5.5769	0.0938	6925.91	2376.00	3739.70
					NPV	11347.67

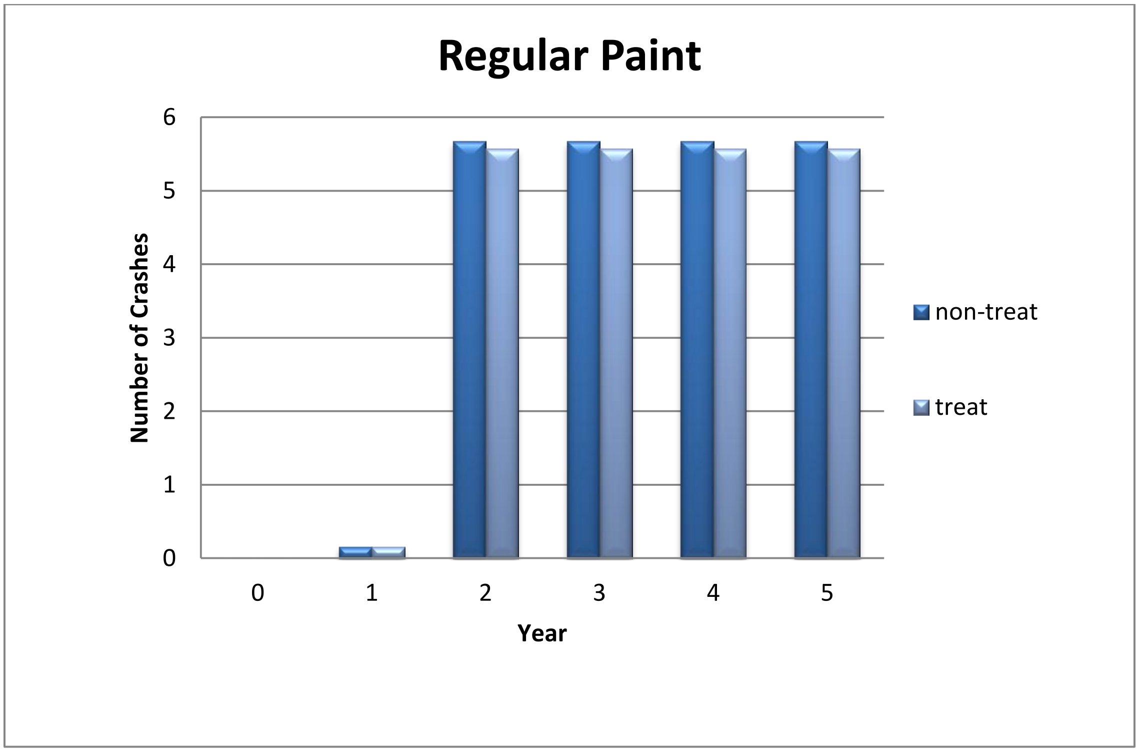

Figure B.22. Paint marking NPV in Range 4

Table B.25. Durable marking NPV in Range 4

Durable						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	6298.73	-6298.73
1	0.1569	0.1479	0.009	664.53	6298.73	-5417.50
2	0.38	0.3583	0.0217	1602.26	6298.73	-4342.15
3	5.6707	0.3378	5.3329	393765.48	6298.73	344456.53
4	5.6707	5.384	0.2867	21169.08	6298.73	12711.23
5	5.6707	4.9532	0.7175	52978.07	6298.73	38367.01
					NPV	379476.41

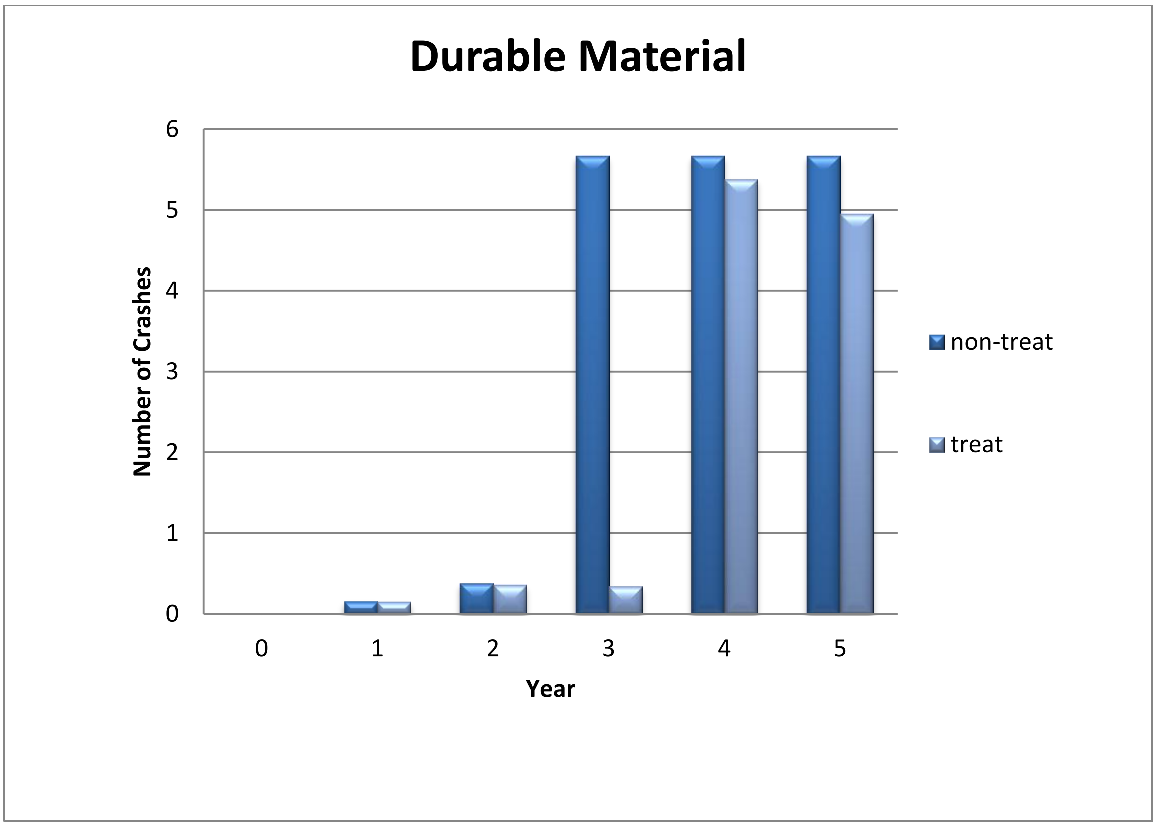

Figure B.23. Durable marking NPV in Range 4

Table B.26. Tape marking NPV in Range 4

Tape						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	10674.28	-10674.28
1	0.1569	0.1239	0.033	2436.62	10674.28	-7920.83
2	0.2235	0.1766	0.0469	3462.96	10674.28	-6667.27
3	0.3184	0.2515	0.0669	4939.70	10674.28	-5098.02
4	1.3635	0.3583	1.0052	74220.98	10674.28	54319.98
5	4.0375	2.3949	1.6426	121284.70	10674.28	90913.70
					NPV	114873.28

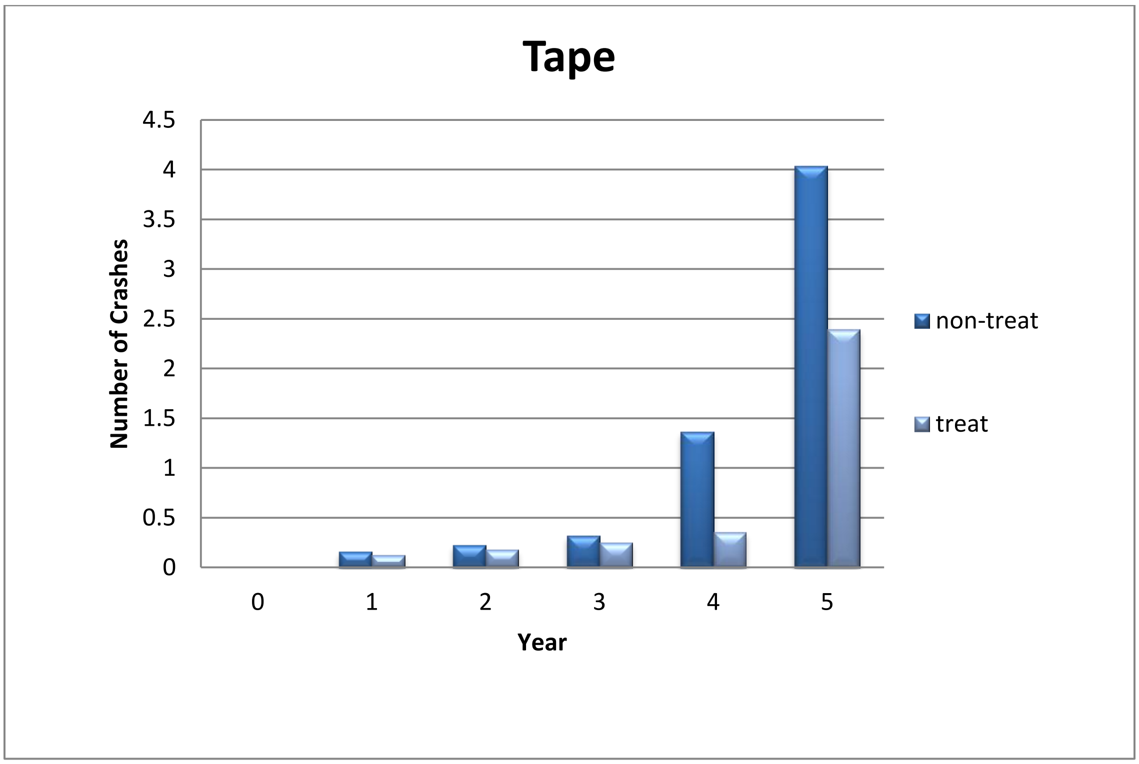

Figure B.24. Tape marking NPV in Range 1

Range 5: 2.50<ACI≤2.75

Table B.27. Reconstruction NPV in Range 5

Reconstruction						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	73581.75	-73581.75
1	0.1251	0.0796	0.0455	3359.58	73581.75	-67521.31
2	0.1366	0.0869	0.0497	3669.70	73581.75	-64637.62
3	0.1493	0.095	0.0543	4009.35	73581.75	-61849.61
4	0.1631	0.1037	0.0594	4385.92	73581.75	-59148.89
5	0.1782	0.1133	0.0649	4792.02	73581.75	-56540.14
					NPV	-383279.32

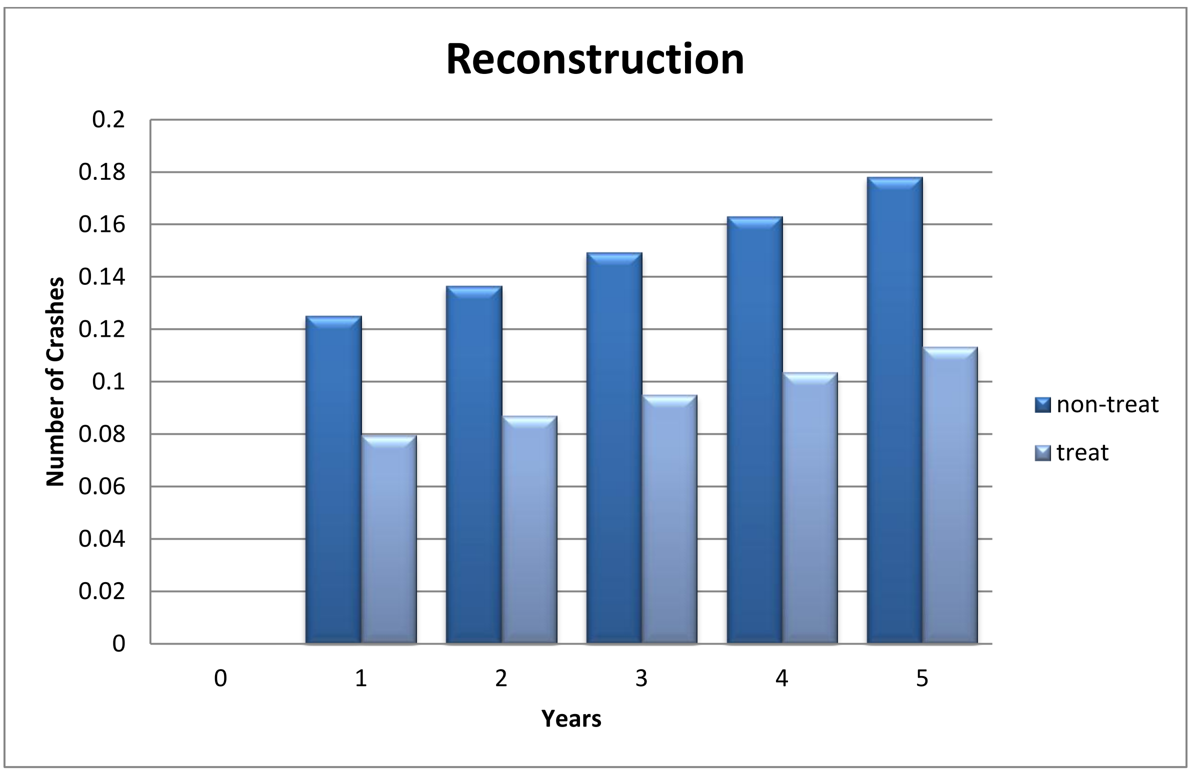

Figure B.25. Reconstruction NPV in Range 5

Table B.28. Major rehabilitation NPV in Range 5

Major						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	61645.47	-61645.47
1	0.1251	0.0796	0.0455	3359.58	61645.47	-56044.12
2	0.1493	0.1133	0.036	2658.13	61645.47	-54537.11
3	0.1782	0.1353	0.0429	3167.61	61645.47	-51986.61
4	0.2127	0.1615	0.0512	3780.46	61645.47	-49463.26
5	0.2538	0.1927	0.0611	4511.44	61645.47	-46960.01
					NPV	-320636.58

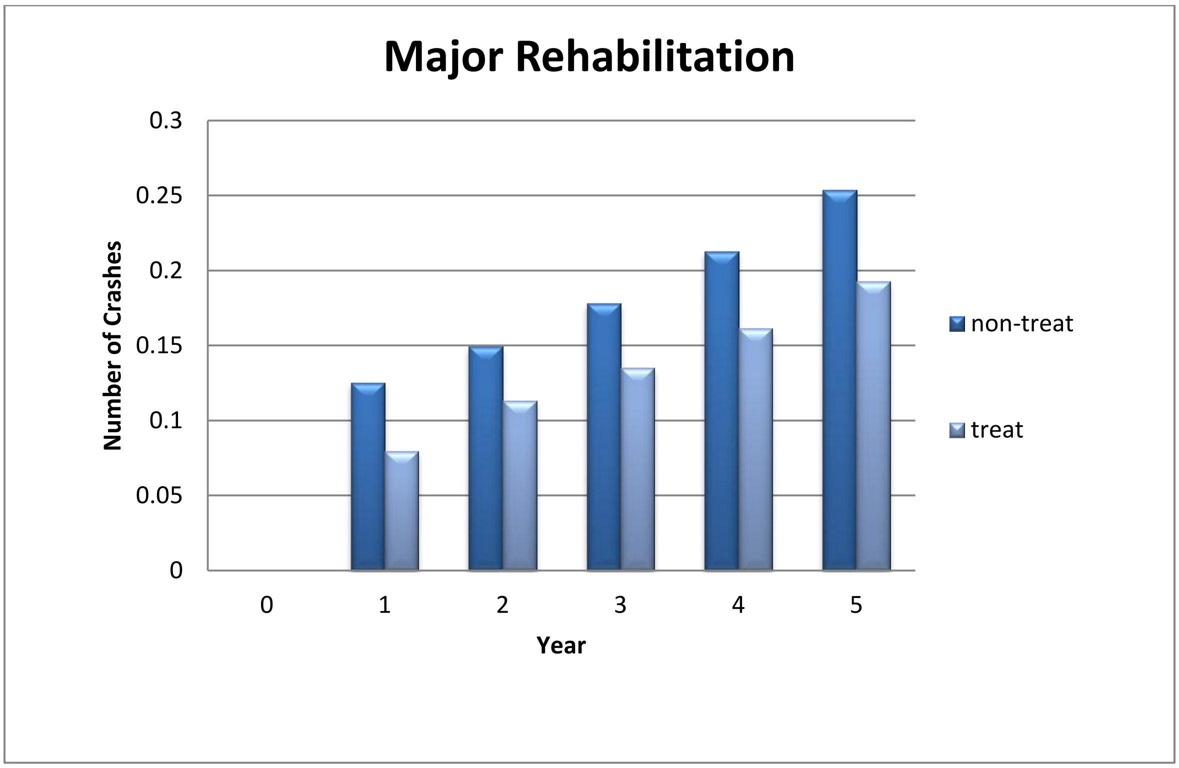

Figure B.26. Major rehabilitation NPV in Range 5

Table B.29. Minor rehabilitation NPV in Range 5

Minor						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	54052.28	-54052.28
1	0.1251	0.0796	0.0455	3359.58	54052.28	-48742.98
2	0.2256	0.1435	0.0821	6062.02	54052.28	-44369.69
3	0.4068	0.2588	0.148	10927.88	54052.28	-38337.44
4	4.7341	0.1435	4.5906	338956.26	54052.28	243537.11
5	5.7663	0.2588	5.5075	406657.43	54052.28	289815.73
					NPV	347850.45

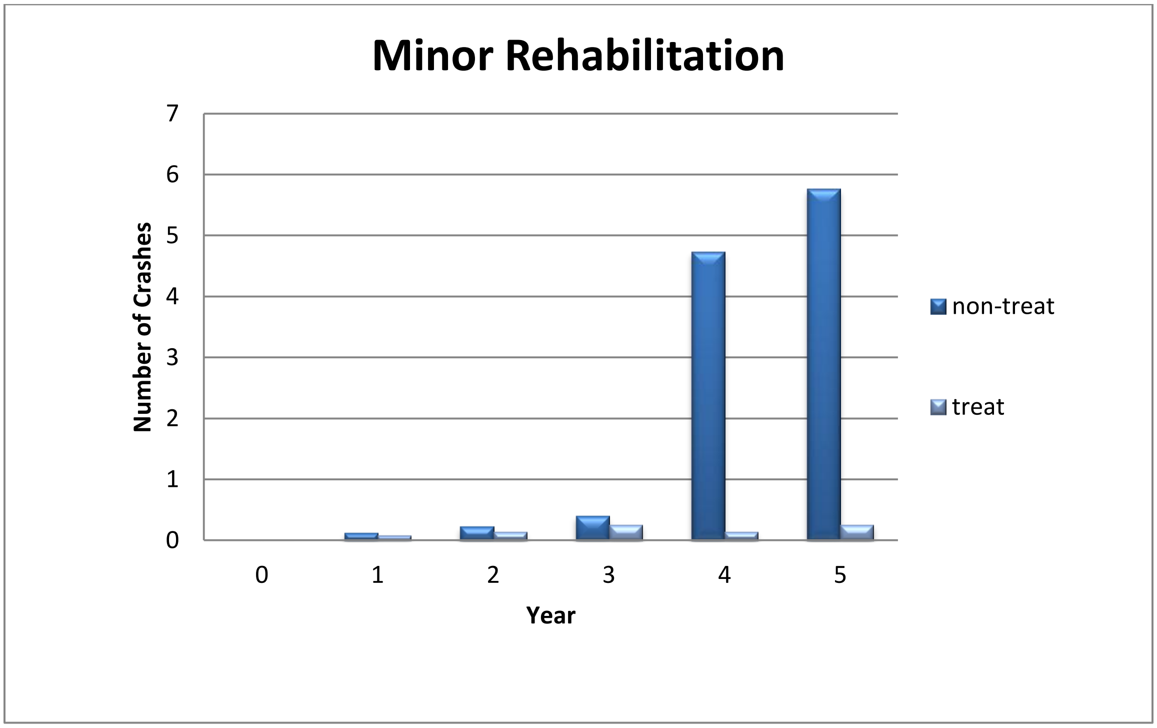

Figure B.27. Minor rehabilitation NPV in Range 5

Table B.30. Paint marking NPV in Range 5

Paint						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	2376.00	-2376.00
1	0.1251	0.1236	0.0015	110.76	2376.00	-2178.12
2	5.7663	5.6709	0.0954	7044.05	2376.00	4315.88
3	5.7663	5.6709	0.0954	7044.05	2376.00	4149.88
4	5.7663	5.6709	0.0954	7044.05	2376.00	3990.27
5	5.7663	5.6709	0.0954	7044.05	2376.00	3836.80
					NPV	11738.71

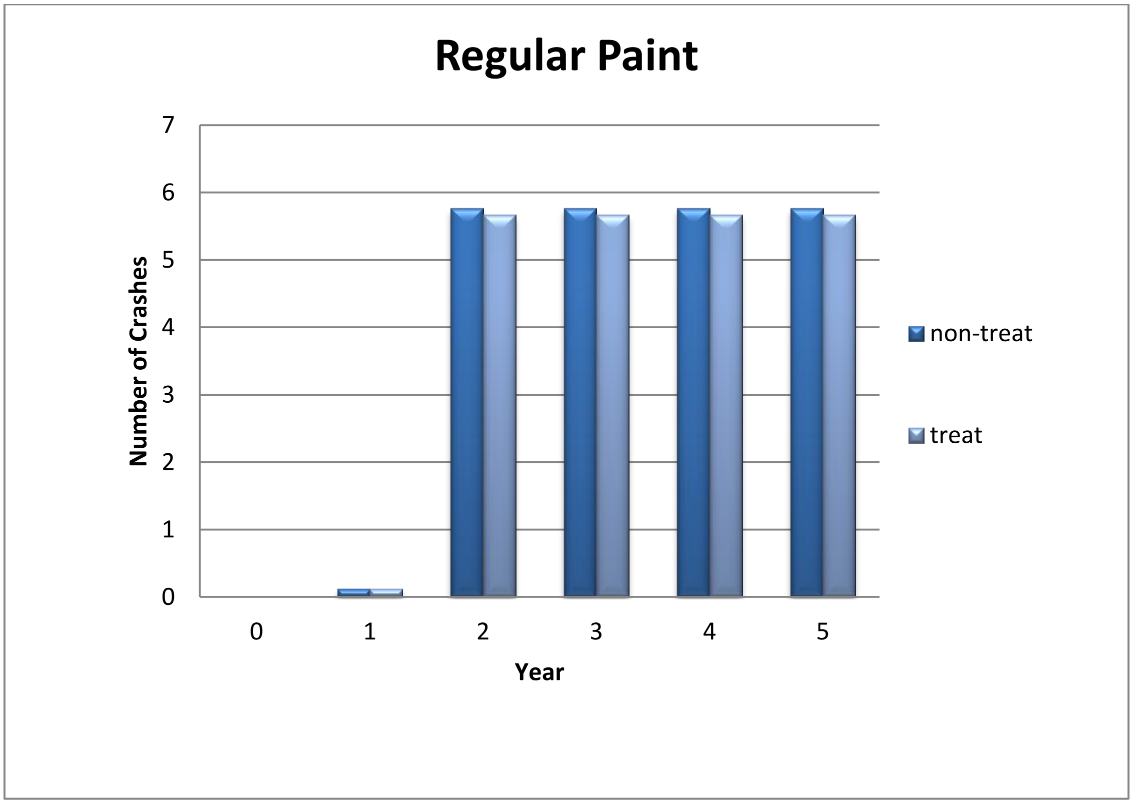

Figure B.28. Paint marking NPV in Range 5

Table B.31. Durable marking NPV in Range 5

Durable						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	6298.73	-6298.73
1	0.1251	0.1179	0.0072	531.63	6298.73	-5545.29
2	0.3029	0.2856	0.0173	1277.38	6298.73	-4642.52
3	4.7341	0.4485	4.2856	316435.96	6298.73	275710.87
4	5.7663	4.6119	1.1544	85237.46	6298.73	67477.16
5	5.7663	4.2429	1.5234	112483.33	6298.73	87276.00
					NPV	413977.49

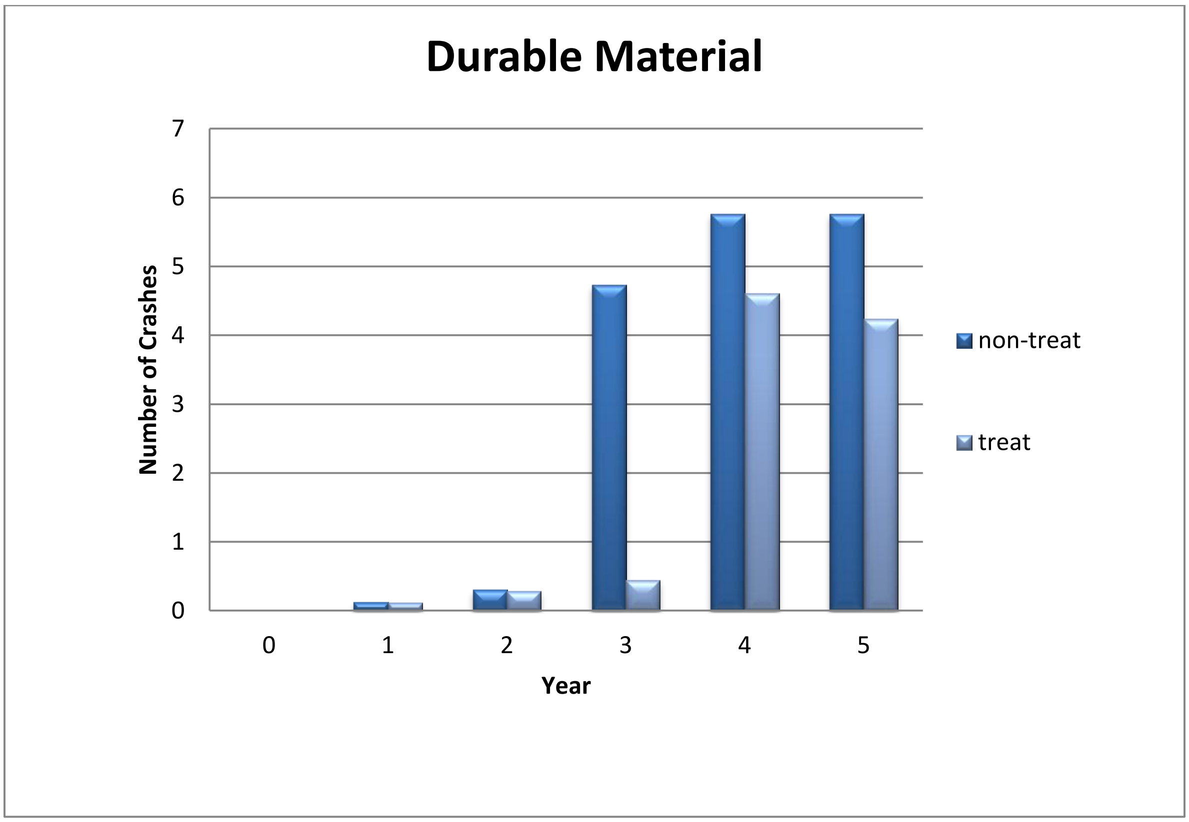

Figure B.29. Durable marking NPV in Range 5

Table B.32. Tape marking NPV in Range 5

Tape						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	10674.28	-10674.28
1	0.1251	0.0988	0.0263	1941.91	10674.28	-8396.51
2	0.1782	0.1407	0.0375	2768.89	10674.28	-7308.98
3	0.2538	0.2005	0.0533	3935.51	10674.28	-5990.74
4	0.3616	0.2856	0.076	5611.61	10674.28	-4327.59
5	2.5209	0.4068	2.1141	156098.86	10674.28	119528.40
					NPV	82830.31

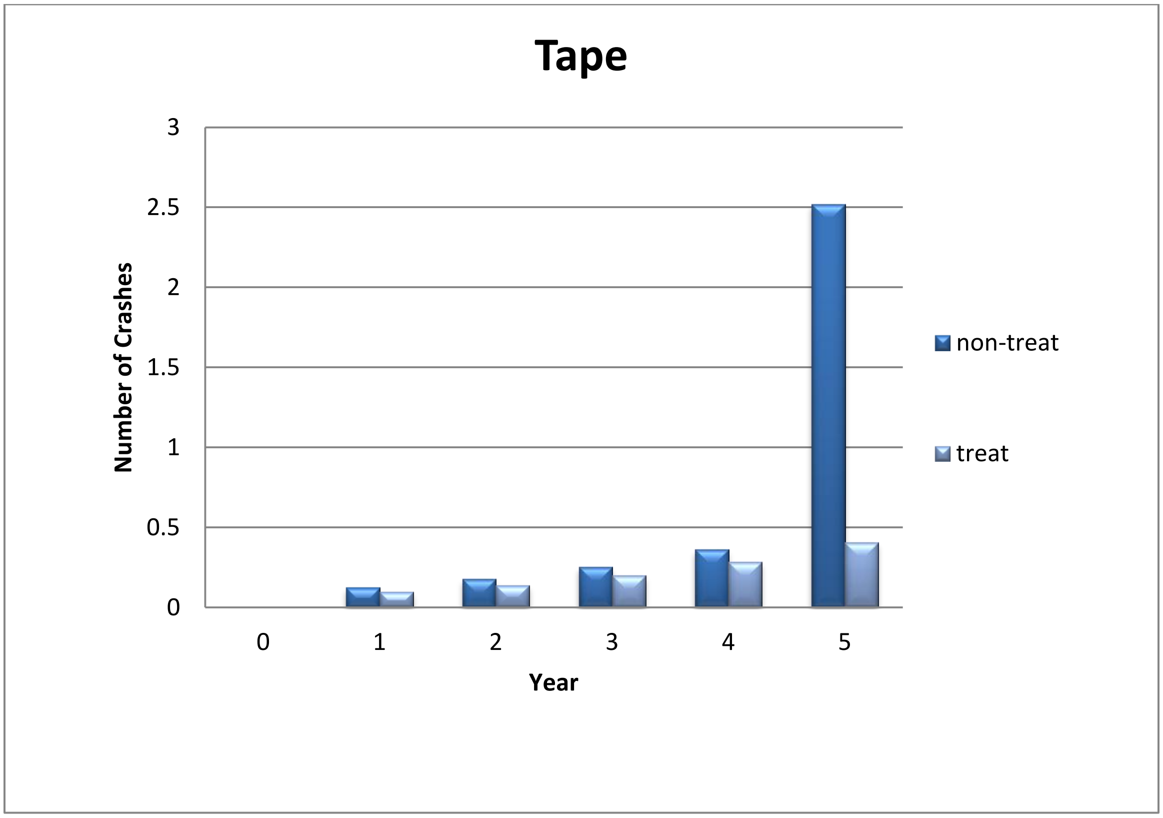

Figure B.30. Tape marking NPV in Range 5

Range 6: 2.75<ACI≤3.0

Table B.33. Reconstruction NPV in Range 6

Reconstruction						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	73581.75	-73581.75
1	0.1251	0.0796	0.0455	3359.58	73581.75	-67521.31
2	0.1366	0.0869	0.0497	3669.70	73581.75	-64637.62
3	0.1493	0.095	0.0543	4009.35	73581.75	-61849.61
4	0.1631	0.1037	0.0594	4385.92	73581.75	-59148.89
5	0.1782	0.1133	0.0649	4792.02	73581.75	-56540.14
					NPV	-383279.32

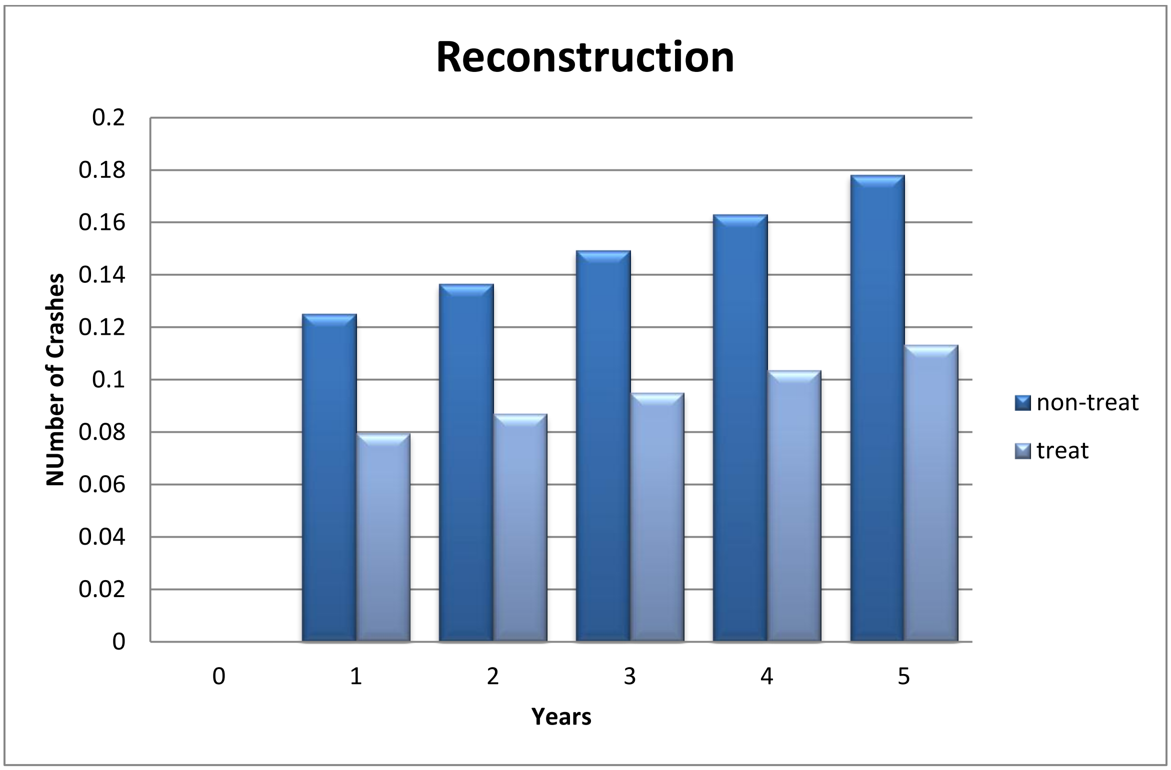

Figure B.31. Reconstruction NPV in Range 6

Table B.34. Major rehabilitation NPV in Range 6

Major						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	61645.47	-61645.47
1	0.0813	0.0672	0.0141	1041.10	61645.47	-58273.43
2	0.097	0.0802	0.0168	1240.46	61645.47	-55847.83
3	0.1157	0.0957	0.02	1476.74	61645.47	-53489.78
4	0.1381	0.1142	0.0239	1764.70	61645.47	-51186.33
5	0.1649	0.1363	0.0286	2111.74	61645.47	-48932.39
					NPV	-329375.24

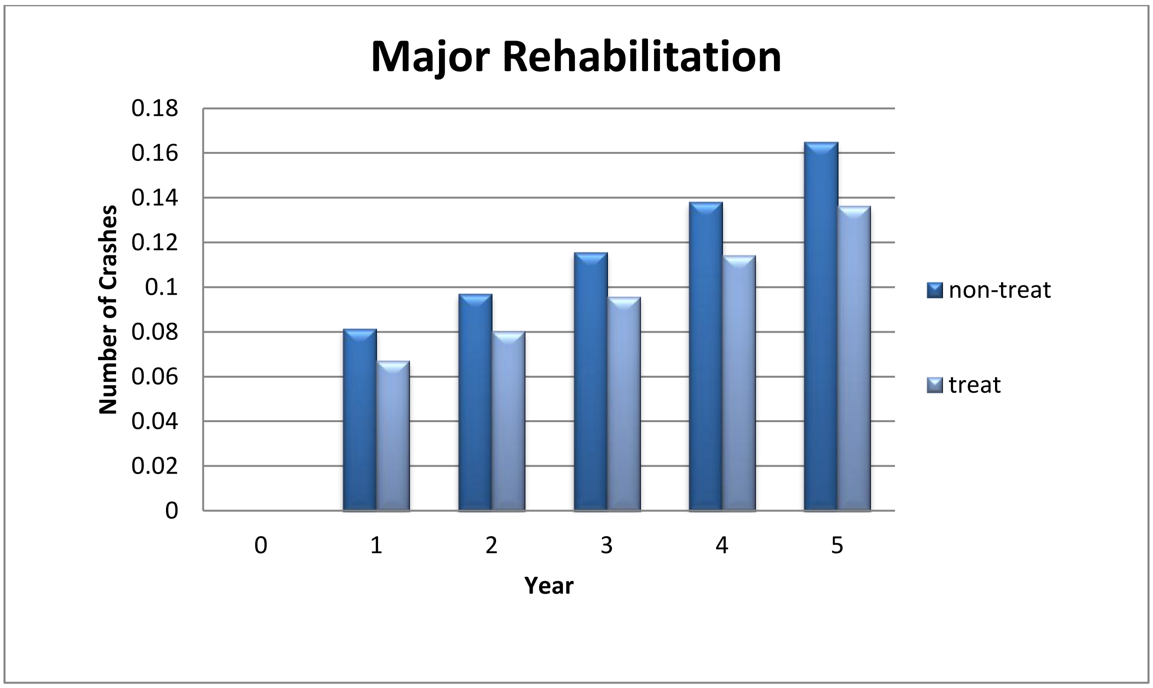

Figure B.32. Major rehabilitation NPV in Range 6

Table B.35. Minor rehabilitation NPV in Range 6

Minor						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	54052.28	-54052.28
1	0.0813	0.0672	0.0141	1041.10	54052.28	-50972.29
2	0.1465	0.1211	0.0254	1875.46	54052.28	-48240.40
3	0.2643	0.2184	0.0459	3389.12	54052.28	-45039.37
4	3.0273	0.1311	2.8962	213846.80	54052.28	136593.02
5	5.4225	0.2184	5.2041	384255.27	54052.28	271402.79
					NPV	209691.47

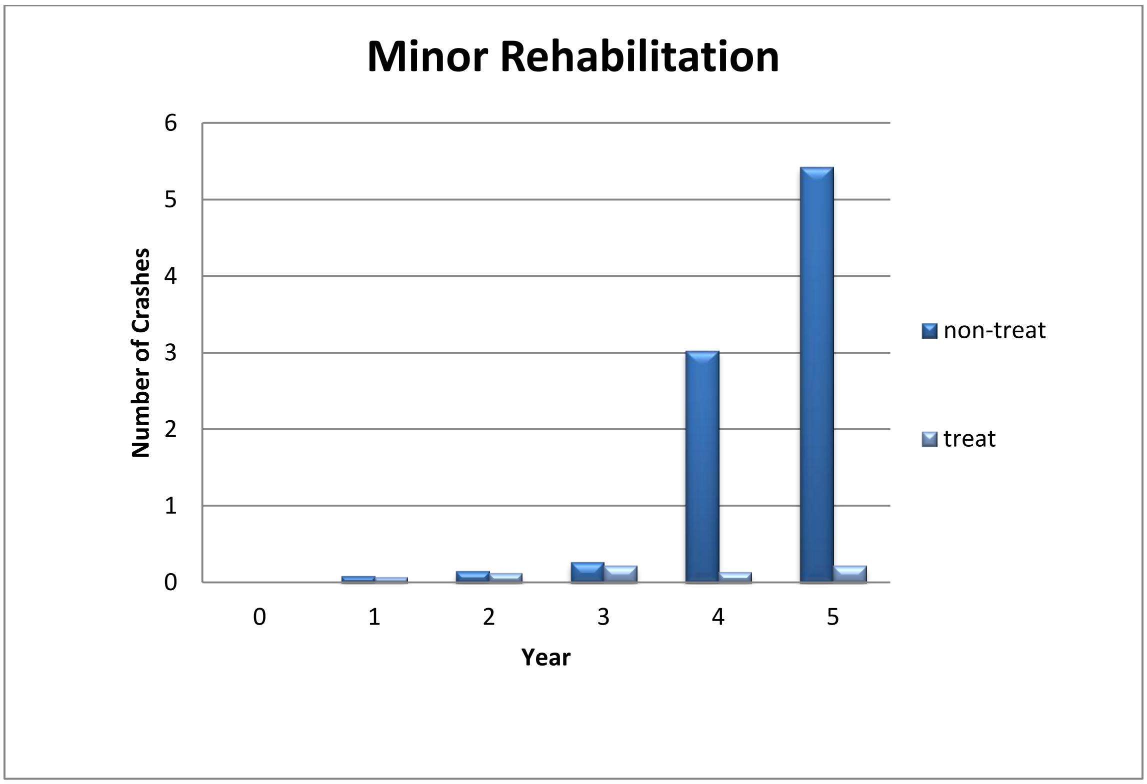

Figure B.33. Minor rehabilitation NPV in Range 6

Table B.36. Paint marking NPV in Range 6

Paint						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	2376.00	-2376.00
1	0.0813	0.0803	0.001	73.84	2376.00	-2213.62
2	5.4225	5.3328	0.0897	6623.18	2376.00	3926.76
3	5.4225	5.3328	0.0897	6623.18	2376.00	3775.73
4	5.4225	5.3328	0.0897	6623.18	2376.00	3630.51
5	5.4225	5.3328	0.0897	6623.18	2376.00	3490.87
					NPV	10234.25

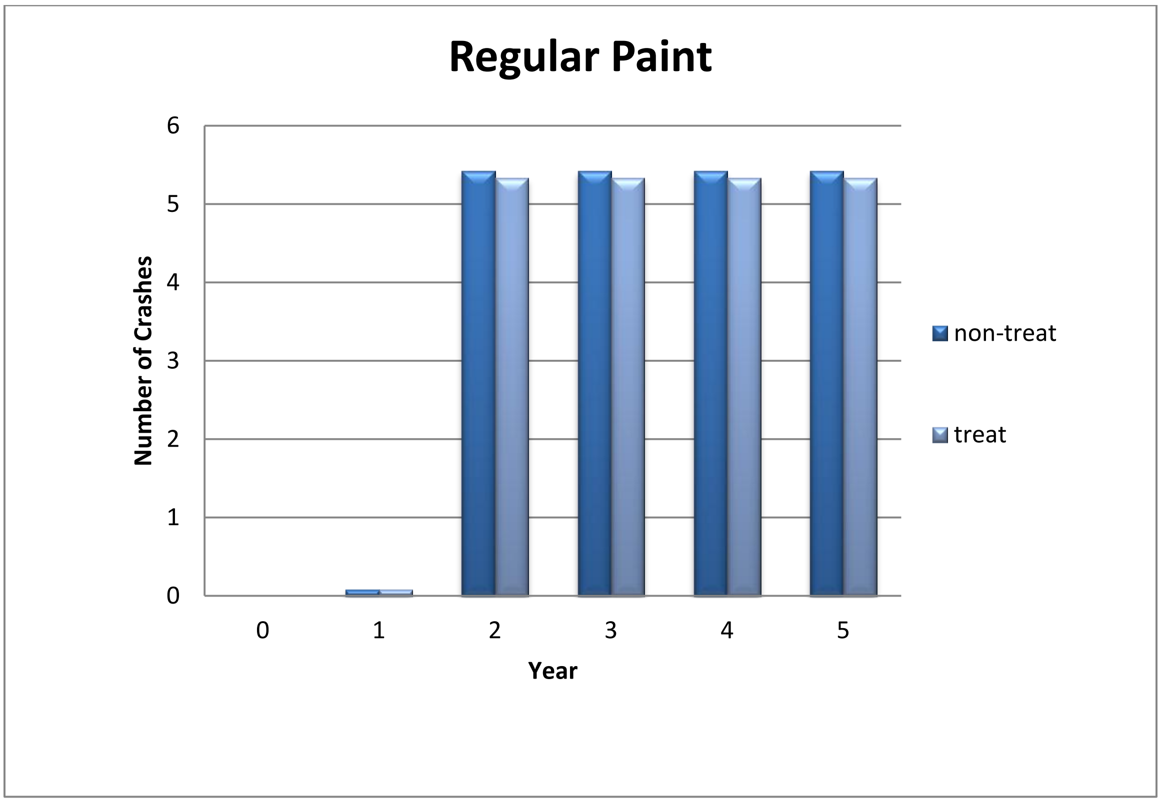

Figure B.34. Paint marking NPV in Range 6

Table B.37. Durable marking NPV in Range 6

Durable						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	6298.73	-6298.73
1	0.0813	0.0767	0.0046	339.65	6298.73	-5729.88
2	0.1968	0.1858	0.011	812.21	6298.73	-5072.60
3	3.0273	0.1751	2.8522	210597.97	6298.73	181621.28
4	5.4225	2.4673	2.9552	218203.18	6298.73	181136.81
5	5.4225	1.1389	4.2836	316288.29	6298.73	254788.82
					NPV	600445.70

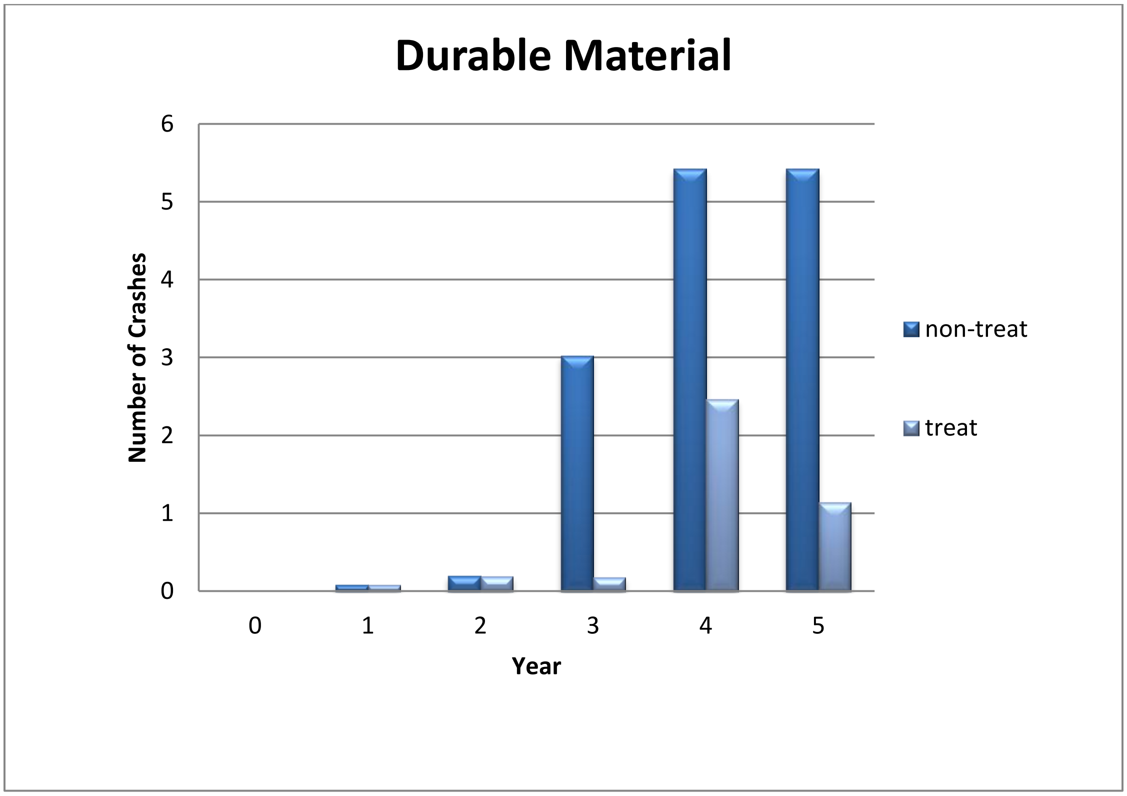

Figure B.35. Durable marking NPV in Range 6

Table B.38. Tape marking NPV in Range 6

Tape						
year	**non-treat**	**treat**	**reduce**	**Benefit**	**Cost (EUAC)**	**PV**
0	0	0	0	0.00	10674.28	-10674.28
1	0.0813	0.0672	0.0141	1041.10	10674.28	-9262.67
2	0.1157	0.0957	0.02	1476.74	10674.28	-8503.64
3	0.1649	0.1363	0.0286	2111.74	10674.28	-7612.07
4	0.2349	0.1941	0.0408	3012.55	10674.28	-6549.28
5	0.3346	0.2766	0.058	4282.55	10674.28	-5253.54
					NPV	-47855.48

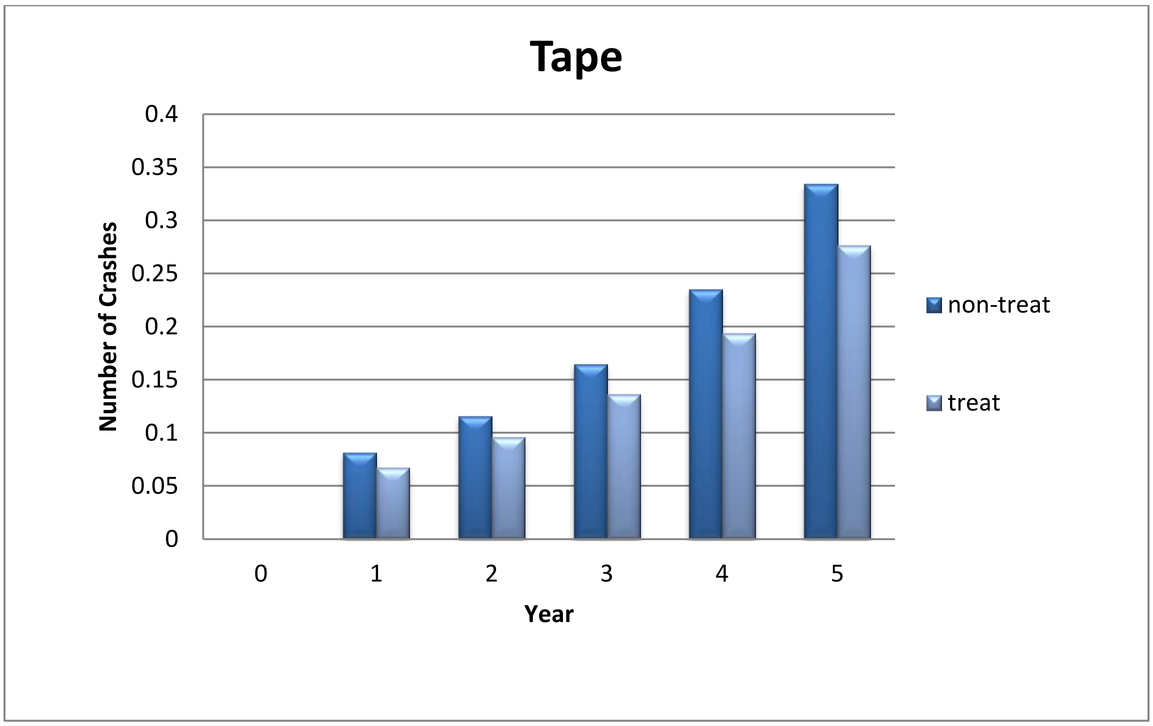

Figure B.36. Tape marking NPV in Range 6