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Developing an Optimization Model for Managing County Paved Roads

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Developing an Optimization Model for Managing County Paved Roads

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ABSTRACT

In Wyoming, most county paved roads were built decades ago without following minimum design standards. However, the recent increase in industrial/mineral activities in the state requires developing an efficient pavement management system (PMS) for local paved roads. The new PMS which is currently being developed depends on the present serviceability index (PSI) as a pavement performance parameter. While developing a PMS for county roads, the primary process shows two major issues related to the pavement management of Wyoming's county roads. The first issue includes the difficulty of measuring some pavement management parameters, such as suitable PSI prediction models for pavement and road roughness. The second issue relates to the high costs of pavement treatments within limited maintenance budgets. This study investigates these issues by developing exclusive PSI pavement prediction models to be more representative for county roads. In addition, smartphones were proposed as a cost-effective solution to minimize the costs of collecting pavement condition data. The initial validation results suggested that smartphones can predict with high certainty the actual values of road roughness represented by the international roughness index (IRI). An optimization methodology was then developed to identify the best mix of pavement preservation projects on county roads for maintaining pavement and improving safety. The maintenance planning takes budget limits, traffic volumes, weighted performance, and associated risk into accounts. It was found that the results from this report will facilitate a statewide implementation of a PMS for counties in Wyoming.

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LIST OF ABBREVIATIONS

Abbreviation	Description
4WD	4 Wheel Drive
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ADT	Average Daily Traffic
ADTT	Average Daily Truck Traffic
ANOVA	Analysis of Variance
ASTM	American Society for Testing and Material
CRF	Crash Reduction Factor
FAST	Fixing America's Surface Transportation
FFS	Free Flow Speed
FFT	Fast Fourier Transform
FHWA	Federal Highway Administration
GIS	Geographic Information system
GM	General Maintenance
GPS	Global Positioning System
IRI	International Roughness Index
LVR	Low-Volume Roads
M&R	Maintenance and Rehabilitation
MPR	Mean Panel Rating
MR&R	Maintenance, Rehabilitation, and Reconstruction
PCI	Pavement Condition Index
PMS	Pavement Management System
PSD	Power Spectrum Density
PSI	Present Serviceability Index
PSR	Present Serviceability Rating
RD	Rut Depth
RTRRMs	Response Type Road Roughness Meters
RUT	Rut Depth
SPF	Safety Performance Function
STIC	State Transportation Innovation Council
SUV	Sport Utility Vehicle
SV	Slope Variance
TSMS	Traffic Safety Management System
VIMS	Vehicle Intelligent Monitoring System
WCCA	Wyoming County Commissioner Association
WYDOT	Wyoming Department of Transportation
WYT^2/LTAP	Wyoming Technology Transfer Center/ Local Technical Assistance Program

EXECUTIVE SUMMARY

In Wyoming, most county paved roads were built decades ago without following minimum design standards. However, the recent increase in industrial/mineral activities in the state requires developing a pavement management system (PMS) for local paved roads. The Wyoming Technology Transfer Center/Local Technical Assistant Program (WYT^2/LTAP) is currently in the process of developing a PMS for county roads. The overall pavement performance parameter is determined in terms of the pavement serviceability index (PSI). The primary steps in the development process show there are two major issues related to the development of a PMS for county roads: the difficulty of predicting suitable PSI prediction models and road roughness, and the high costs related to pavement maintenance planning within limited budgets. The first part of this study deals with the development of exclusive county road PSI models. The developed PSI models for county roads are based on the international roughness index (IRI), the pavement condition index (PCI), and rut depth for flexible pavements only. Ten panelists from Wyoming rated 30 pavement sections randomly selected at different distress levels using two vehicles (SUV and sedan). Regarding the rating process, the statistical analysis indicated that the seating position, age, and gender were not significant to the rating process. However, the vehicle's type was significant. One model (sedan) was proposed to be used in the county roads' PMS. The newly proposed model explains 80% of the variations in the PSI values of county roads (Adjusted $R^2 = 0.80$). In addition, the new model seems to provide more realistic representation of county road conditions.

In terms of collecting pavement condition data using innovative practices, modern smartphones are proposed as a cost effective solution to minimize the costs of collecting road roughness. Smartphones are equipped with many useful sensors, such as gyroscopes, magnetometers, GPS receivers, and 3D accelerometers. A smartphone 3D accelerometer was used for collecting a vehicle's vertical acceleration data. By using various signal processing and pattern recognition techniques, cross correlations, Welch periodograms, and variance analyses were conducted on a case study in Wyoming to predict road roughness in terms of IRI. The smartphone data were collected over 20 roadway segments. The selected segments have various lengths and geometric features reflecting the actual roadway segments under any PMS. The measured signals (time series acceleration data) were identified and correlated with the actual IRI values. A validation analysis was also conducted to measure the reliability of this methodology. The initial validation results suggested that the smartphones used could predict with high certainty the actual IRI values. In addition, the difference between the predicted and the actual IRI values was not statistically significant.

The process of maintaining county roads requires enhancement in both the PMS and traffic safety management system (TSMS). A PMS selects the list of projects that provide the most benefit to society within a limited budget. Similarly, a TSMS is also a strategic and systematic process to improve traffic safety within a limited budget. The TSMS uses the limited funding to identify the best set of safety projects expected to help to reduce crashes. In this report, an optimization methodology was developed to identify the best mix of pavement preservation projects on county roads for maintaining pavement and improving safety. The methodology developed in this research can be used to identify the best mix of pavement preservation projects within a certain budget. It will ensure that higher traffic roadways have higher priority. It will also maximize the weighted average PSI and minimize the risk. The risk is determined by the life-cycle cost of pavement and the variation in maintenance cost of each treatment type. Six possible treatment options were assigned for county paved roads using a developed decision tree. The maintenance decision was then optimized through a multi-year optimization analysis considering the objective functions. In Laramie County, Wyoming, a case study of 17 county roads divided into 23 segments was investigated. A statewide analysis was then conducted to define critical budgets of managing county roads using both PMS and TSMS. The findings will help lawmakers make funding decisions to preserve the local pavement network.

1. INTRODUCTION

A well-functioning transportation infrastructure is essential to economic growth. According to Moving Ahead for Progress in the 21st Century Act (MAP-21), each state is required to develop a pavement management system (PMS) to improve or preserve the present pavement condition and the performance of the system (FHWA, 2014). PMS is an assessment tool for decision makers to optimize allocation of available resources and prioritize the different maintenance and reconstruction projects. In the state of Wyoming, 27,831 miles of roadway is owned and maintained by federal, state, and local entities. Of these roads, 63% are maintained by local governments not currently part of the Wyoming Department of Transportation (WYDOT) PMS (Saha and Ksaibati, 2015). Developing a PMS for county roads requires building a comprehensive pavement management database and maintenance planning that includes different roadway condition indices and decision-making tools.

Several issues should be investigated to develop different models designed specifically for managing county paved roads. These models consider the local and urgent needs of managing these roads by local agencies. Among these issues, specific pavement performance curves should be developed to reflect the actual conditions of pavement performance in terms of a present serviceability index (PSI). In addition, innovative techniques of measuring pavement management indices using smartphone applications are being evaluated within efficient and affordable practices for roadways. For decision-making, maintaining county roads efficiently requires an improved PMS and a traffic safety management system (TSMS). A PMS selects the list of projects that provides the most benefit to society within a limited budget. Similar to a PMS, a TSMS is also a strategic and systematic process to improve traffic safety within a limited budget. The TSMS uses the limited funding to identify the best set of safety projects expected to help to reduce crashes.

In this study, pavement performance and roughness indices are measured using a pavement condition rating and smartphone applications. The necessary data used in this study have been collected since 2014. In addition, decisions made regarding pavement maintenance and road countermeasures are optimized through multi-year optimization models. Various aspects of analysis were investigated, including PSI prediction modeling and validations, developing a capital improvement plan, determining appropriate budget, and efficient allocation of budgets. The findings of this study will be presented to the Wyoming Legislatures. Their feedback will be implemented to produce actual budget needs to maintain and preserve local paved roads in the State of Wyoming.

1.1 Background

Many county roads were built over 40 years ago and have had inconsistent maintenance, resulting in poor overall road conditions. Moreover, the growth of oil and gas industries has increased truck traffic on many county roads (Huntigon et al., 2013). Increased truck traffic, no maintenance database, and limited funding necessitate the development of an innovative PMS to use resources more efficiently for local roads. In 2014, the Wyoming County Commissioner Association (WCCA), WYDOT, and the State Transportation Innovation Council (STIC) supported funding a project to develop a comprehensive database for a PMS of county paved roads. As a result, a comprehensive effort was conducted by the Wyoming Technology Transfer Center (WYT^2/LTAP) to collect roadway inventory data, pavement condition data, and roadway thicknesses. The pavement condition data include rut depths, international roughness index (IRI), pavement condition index (PCI), and PSI. The PSI ranges between 0 for worst conditions and 5 for best conditions. PSI can be considered a pavement performance parameter. However, each state's DOT uses a different pavement performance model to estimate the overall serviceability of pavements. WYDOT has already developed a PSI model to predict the expected PSI for the state's highway system. This model is currently used for all road classes in the state. In the WYDOT model, PSI is considered the dependent variable. The independent pavement condition parameter variables include IRI, rut depth, and PCI.

When applying the WYDOT PSI model on county roads, it was found that 68% of county roads are in very poor condition (PSI <2.0), where there is only a very small percentage of very poor roads in the secondary, primary, and interstate systems. The alarmingly high percentage of county road miles in poor shape requires that an investigation be performed to determine the suitability of using the WYDOT PSI model on county roads.

In addition, the state of Wyoming is currently considering many low-cost approaches that guarantee the development and sustainability of the PMS for local roads. One approach considers collecting data every two or three years. Another approach considers collecting the data for only one part of the local road network and predicting the remaining part based on the network's performance and multiple imputation analysis (Hafez et al., 2016). The use of modern smartphones appears to be an appealing approach for reducing the cost of measuring local road roughness. These smartphones are equipped with many useful sensors, such as gyroscopes, GPS, and 3D (i.e., 3-axis) accelerometers. Therefore, the ability of a smartphone's 3D accelerometer in identifying and estimating local roads' IRI will also be investigated.

Furthermore, the WYT^2/LTAP is in the process of developing a statewide PMS to manage local roads more efficiently. In this study, an optimization methodology was developed to identify the best set of pavement maintenance projects within a limited budget. The developed methodology was implemented statewide for a county paved road network consisting of 2,250 segments totaling 2,444 miles. The necessary data used in this study were collected in 2014. Various aspects of analysis were investigated, including developing a capital improvement plan, determining appropriate budget, and efficient allocation of budgets.

Most optimization models concentrate on state highways and interstate systems. Most local agencies do not have the expertise or the resources to conduct optimization on their networks. In Wyoming, WYDOT manages a total of 6,844 miles of state highways and interstates utilizing its PMS, while local governments manage the county roads using their engineering judgment and without any PMS. The optimization models available in the literature cannot be used to manage county roads because these roads have lower standards, carry lower traffic volumes, and, most importantly, do not receive adequate funding to maintain them. In addition, some of the input parameters required to utilize existing optimization models are not available for county roads. These parameters include road width, traffic volume, and deterioration models. The maintenance decision trees are also different for county roads as compared with state highway systems. Moreover, the existing systems for managing county roads do not utilize efficient optimization techniques. In order to address these specific issues, an innovative optimization methodology was developed in this study to manage the local roads.

1.2 Research Objectives

This study relies on two experiments for riding quality survey and road roughness measurements using smartphones. These tools are integrated with decision-making optimization models in order to achieve the following:

- Evaluate the suitability of using the WYDOT PSI model to predict the serviceability or the performance of county paved roads.
- Provide a better description of the pavement condition for county roads according to Wyoming's local perspective.
- Evaluate the ability of smartphones in returning reliable road roughness measurements as a cost effective solution.

- Identify the best mix of pavement preservation projects within budget constraints, maximizing traffic (passenger and truck traffic) on treated roads, maximizing the weighted average PSI, and minimizing the risk.
- Determine critical budgets of maintaining county roads for pavement preservation and safety improvement.
- Help lawmakers assign appropriate maintenance funding to preserve the condition of the county road network in Wyoming.

1.3 Report Organization

The various tasks of this study are broken down to the following chapters:

Chapter 1	The report begins with a brief introduction showing the research background, study objectives, and report format.
Chapter 2	The literature is reviewed in this chapter. The chapter provides the required knowledge to understand the different parts of this study. It also summarizes the literature on previous riding quality experiments and major attempts to measure IRI using a smartphone's internal sensors. Different terminologies related to PMS, roadway condition indices, and PMS challenges at the local level are introduced. A brief background about optimization analysis is also introduced showing methods currently employed in different applications of a PMS.
Chapter 3	This chapter presents the overall research methodology applied to develop serviceability prediction models for county paved roads and IRI prediction analysis using smartphones. The steps followed in designing the experiments of ride quality survey and smartphone measurements are introduced in this chapter. It also formulates the different optimization problems set in the maintenance planning of county paved roads in Wyoming.
Chapter 4	The PSI modeling for county roads is analyzed and introduced in this chapter. Multiple steps of regression analysis are conducted to fit the PSI prediction models using two types of vehicles for riding quality surveys. The chapter also provides information for validating the developed models and model comparison with WYDOT models.
Chapter 5	Evaluating IRI measurements using smartphones is presented in this chapter. Two main steps are implemented for pattern recognition analysis combined with model development and models validation. These steps are presented in this chapter showing the applicability of such innovative practices for county roads.
Chapter 6	The application of optimization analysis for maintenance planning is introduced in this chapter. The results from risk-based analysis show the optimized set of maintenance projects aimed to maximize the overall pavement performance of county paved roads. This chapter also defines critical budgets for developing multi-year maintenance plans for pavement preservation and road countermeasures for both PMS and TSMS.
Chapter 7	This chapter provides the summary and conclusions reached based on the analysis of this study. It also presents the recommendations for Wyoming's county paved road management in addition to potential future research to enhance the results and contributions of this study.

2. LITERATURE REVIEW

This chapter provides the required knowledge to understand the parts of this study. The terminologies related to PMS, roadway condition indices, and PMS challenges at the local level are introduced. In addition, studies related to pavement serviceability concept and riding quality surveys are summarized. The development of IRI, the most widely accepted index to describe pavement roughness, is also presented. Studies that tried to estimate pavement roughness using smartphones are also discussed in detail. Finally, various highway classification systems are presented in detail.

2.1 Pavement Management System

Pavements are the most important part of any transportation infrastructure system. Pavement networks facilitate the national and international trade movements that assist the nation's economic growth. Reports show that highways are responsible for 70% of freight shipped in 1993 (AASHTO, 2001). While pavements continue to age and deteriorate with time, agencies have to employ inordinate amounts of funds to maintain their pavement network in acceptable condition. Figure 2.1 shows pavement performance with time combined with the approximate rehabilitation cost to maintain a serviceable pavement condition. Due to the many arising budget constraints, a pavement management system (PMS) formulates an appealing way for running roadway networks (Wolters et al., 2011).

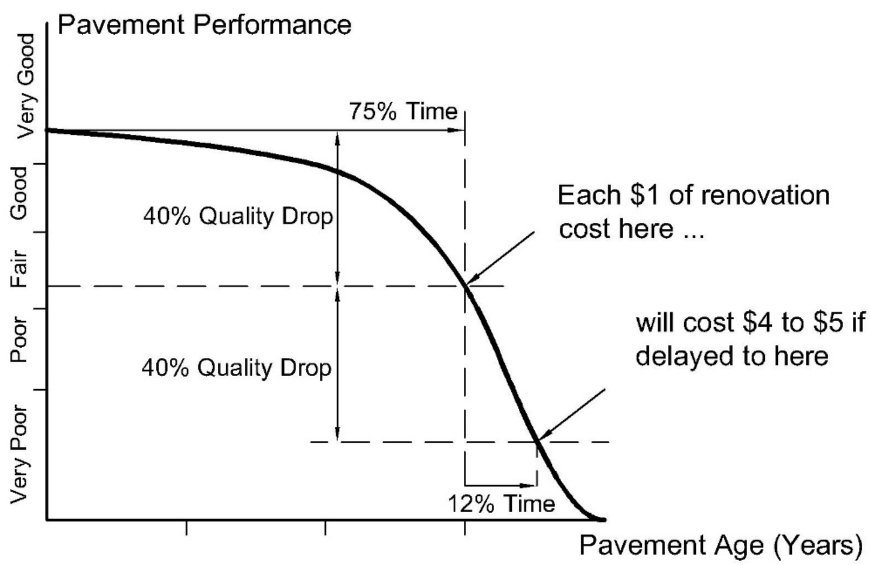


Figure 2.1 Pavement Performance vs Age (Shahin and Walter, 1990).

PMS is an assisting tool that helps decision makers determine the best practices and better funding allocation strategies to maintain roadway networks in a serviceable condition according to the driving public's perspective. The FHWA clearly defines PMS as, "A set of tools or methods that can assist decision-makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in a serviceable condition" (AASHTO, 1993). Consequently, adopting PMS guarantees a systematic process for managing roadway networks. The current network conditions, targeted serviceability levels, funding needs, future roadway network performance, and best pavement preservation practices are all defined as part of the PMS implementation process. The PMS results in many recommendations that are evaluated based on practical judgment to deduce the final investments related to the roadway network. Hence, these decisions are intended ultimately to maximize the service life of the pavement network

(Wolters et al., 2011). Accordingly, PMS formulates an intersection point between engineering and politics. There are two major levels of PMS: network and project levels. The network level is concerned with managing the entire network as one piece, while the project level is more about engineering and technical aspects of specific sites (Kay et al., 1993).

According to Moving Ahead for Progress in the 21st Century Act (MAP-21), each state is required to develop a PMS to improve or preserve the present pavement condition and the performance of the system (FHWA, 2014). All state DOTs already have their own pavement management systems. The Wyoming Department of Transportation (WYDOT) utilizes its PMS to maintain 6,844 miles of interstate and state highways. Currently, there is no PMS or road maintenance database for the 63% of roads maintained by Wyoming local governments. In a recent study by Huntington et al, 2013, a recommendation was made to establish a pavement management system for local roads. This proposal concentrates on establishing an optimization procedure for managing the 2,550 miles of county paved roads shown in Figure 1. The proposed PMS for county roads will be developed considering local factors and traffic conditions, which are significantly different from the state managed roadways (Wolters et al., 2011).

2.2 Components of Pavement Management System

According to the AASHTO (1990), building PMS requires three main components: (1) data collection, (2) data analysis, and (3) update or feedback. These components are described briefly in the following subsections.

2.2.1 Data Collection

Developing a comprehensive database is a vital step in building any PMS (Pierceet al., 2013). PMS uses data from various resources. Generally, the collected data include network inventory, historical pavement condition, traffic data, and cost data. The inventory data include basic information about the network, such as location, number of lanes, pavement width, drainage information, functional classification, and route designation. These data are collected for every segment included in the network. Inventory data normally represent the stationary type of data, which need to be entered once to the database. However, the amount of the collected inventory data depends on the complexity level of the adopted PMS (AASHTO, 2001).

Pavement condition data are considered the most expensive element needed to complete the PMS database, as it should be updated regularly to reflect the current network conditions. The collected pavement condition data are used in the agency's PMS to expedite the comparison process between the different pavement sections; this allows for the selection of the most cost effective combinations of sections and treatments. Hence, it is a way of supporting the decision making process (Pierce et al., 2013). Normally, roughness (ride quality), skid resistance, structural capacity, and surface distresses (i.e., rutting, cracking) comprise the pavement condition data part of any PMS (AASHTO, 2001).

Cost data should include basic information related to the pavement construction and rehabilitation costs as a minimum. However, in a more sophisticated PMS, cost data may include information related to user costs. This allows the estimation of the different user costs associated with the different pavement types and construction sequences.

Furthermore, including traffic data (volume and weight) is very important to the management process. Highway traffic capacity, pavement deterioration, and structural-load carrying capacity are highly affected by the traffic volume. Hence, it highly influences the decision making process. Regardless of their importance, traffic data are normally neglected by pavement engineers. This has many negative impacts on the PMS, which is being adopted (AASHTO, 2001).

The collected types of data are compiled in a single comprehensive database. This database is the base building block of PMS. In addition, it provides the required information to support the implementation of data analysis and feedback processes to complete the PMS.

2.2.2 Data Analysis

PMS is intended to help decision makers identify the most cost effective maintenance, rehabilitation, and reconstruction (MR&R) strategies. In order to select the best MR&R practices, there are three main analysis methods currently used to analyze the collected data. These methods are listed in an increasing order of sophistication as follows:

2.2.2.1 Pavement Condition Analysis

This method is based on combining pavement condition data into a single score or index that represents the overall pavement condition. The combining process includes weighting factors that reflect the different distress severity. The outcome of this process represents the pavement condition as a single index on a defined scale (i.e., from 0 to 100). For example, the pavement condition index (PCI) combines many different distresses, such as cracking, raveling, and shoving. The PCI ranges from 0 to 100, with 100 representing the best pavement condition and 0 representing the worst pavement condition.

This method is considered a simple way to present the health of the pavement network to legislators. Also, it eases the ranking process of the roadway segments in order to identify the MR&R practices and estimate the average required costs (Alkire, 2016).

2.2.2.2 Priority Assessment Models

In this method, a life cycle cost analysis over 20 to 30 years is performed to determine the optimal MR&R strategies. Using a “bottom up” approach, projects are defined and prioritized. This approach starts by processing the small or the subordinate network units toward the top or the most important part of the network. Normally, the benefit/cost ratio is used in the prioritization process in addition to the cost effectiveness measures. This type of analysis yields a list of maintenance projects with their estimated costs. This method can predict the funding needs to achieve a specific network performance level. Priority assessment models include performance models that predict specific pavement condition parameter based on different variables such as, age, traffic, and environment (Alkire, 2016).

2.2.2.3 Optimization Models

Optimization models formulate the most sophisticated level of analysis that can be performed in any PMS. However, they provide a way to evaluate the entire pavement network concurrently. This method identifies the MR&R projects that maximize or minimize specific criteria (i.e., cost). This optimization process is performed within defined boundaries such as available budgets or anticipated performance levels. Optimization models use a “top down” approach, in contrast with the priority assessment models.

2.2.3 Feedback

The feedback process is very important when it comes to reliability and credibility of the followed PMSs. In this process, the practical engineering judgment has a very important role. For example, the actual MR&R costs are compared with those costs projected through PMS processes, in addition to the predicted and actual pavement performance criteria. If discrepancies are found, relevant PMS models and tools must be revised accordingly. This helps in measuring the effectiveness of the used methods and helps improve the implemented PMS. Moreover, it helps in informing and calibrating the used system. Figure 2.2 shows a schematic representation of the PMS components and their expected outcomes.

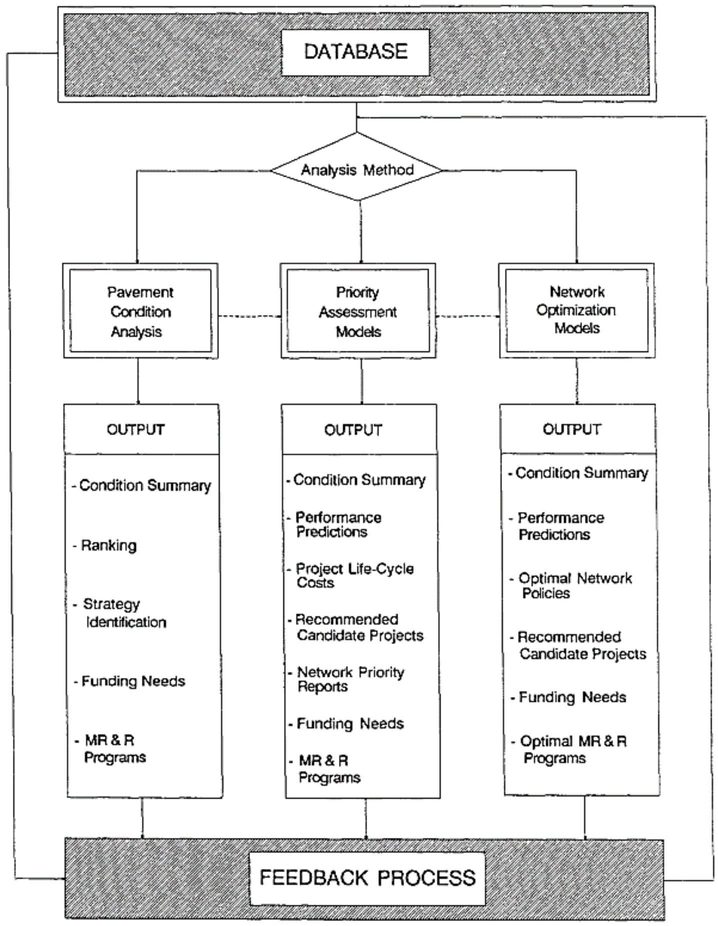


Figure 2.2 A Schematic Representation of PMS components (Alkire, 2016)

2.3 Pavement Management Levels

There are two major levels that must be included in any PMS: network and project levels. Each level is concerned with managing a different level of the roadway network. For example, the network level provides general strategies and solutions related to the entire network, while the project level is concerned with more particular decisions related to specific projects. Therefore, the details level of the required data is higher and more challenging at the project level than the network level.

Network level pavement management provides support for planning, budgeting, and network analysis. On one side, the main outcomes of network level management include identifying the various funding needs related to maintenance and rehabilitation strategies, in addition to proposing many future funding options and their related impacts on the network. This includes defining potential projects for maintenance and rehabilitations works. On the other side, the project management level deals directly with the selected projects. This type of management is intended to provide the most cost effective strategies (i.e., design, maintenance, rehabilitation) within the assigned budgets (Haas et al., 1994). Moreover, this management level provides support at the preliminary design level. Additionally, it may include the quality control/assurance during the construction of the selected project.

In summary, network pavement management allocates funds for the different projects. The project level management then makes the best treatment selection within the previously allocated funds through the network level management. Figure 2.3 shows the main differences between the network and project management levels in PMS.

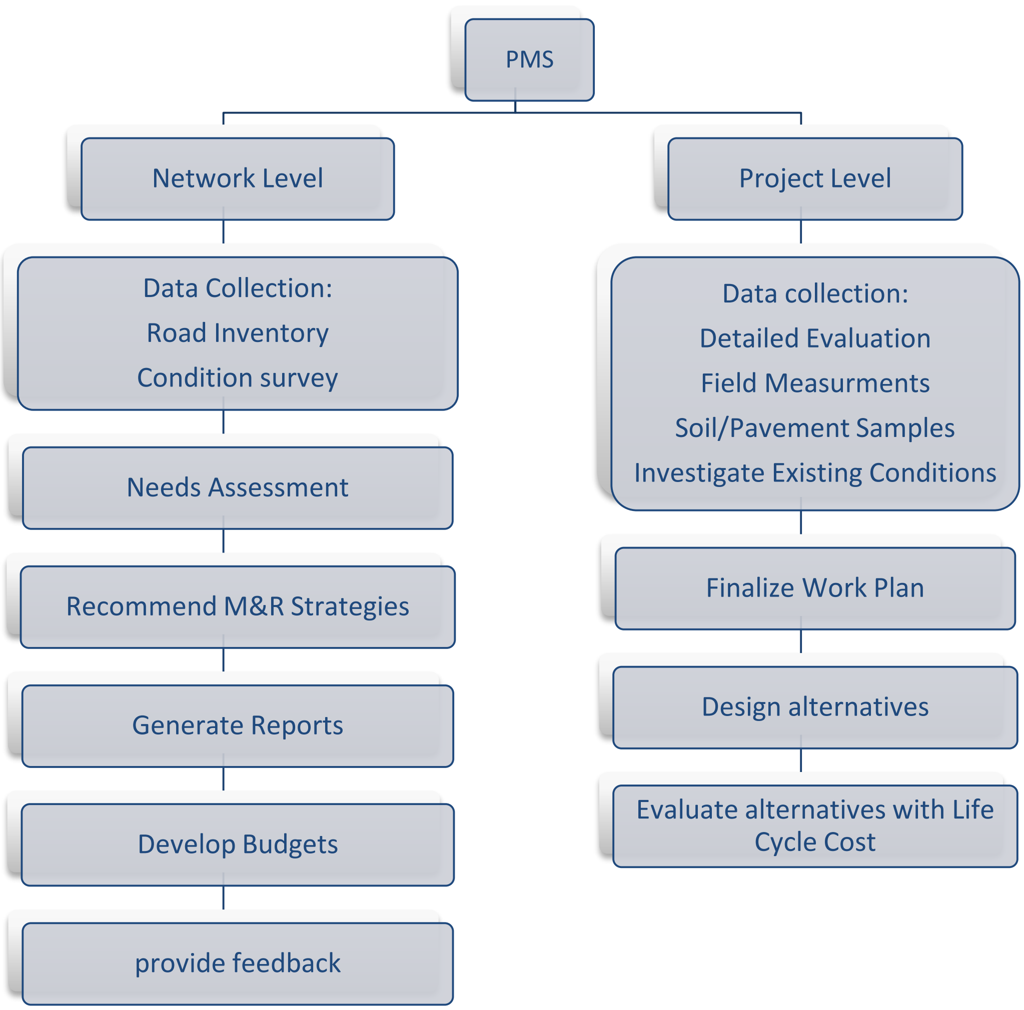


Figure 2.3 Network Level vs Project Level PMS (Schram, 2008)

2.4 Pavement Condition Indices

Pavement condition analysis is considered the simplest type of data analysis. However, it formulates the basic block for any further analysis (Kay et al., 1993). Currently, there are three main pavement condition indices resulting from this elementary analysis, namely PCI, IRI, and rutting. These indices are discussed in detail as shown in the following subsections.

2.4.1 Pavement Condition Index

PCI is a simple way to represent how healthy the pavement is in the means of a single numerical value. The PCI is developed by the U.S. Army Corps of Engineers and adopted by many agencies like the Federal Aviation Administration, U.S. Department of Defense, American Public Works Association and ASTM (Shahin, 1994). The PCI provides numerical ratings for pavement condition on a scale from 0 (worst) to 100 (best). Moreover, PCI value reflects the type, extent, and the severity of the pavement surface distresses. The severity of a distress is classified into three categories: low, medium, and high. In order to calculate PCI, a subjective distress survey is required. Table 2.1 summarizes the different pavement defects that should be measured during the distresses survey.

Table 2.1 Distress Types for Asphalt Concrete-Surfaced Pavement (Hafez, 2015)

Category	Distress Type	Unit of Measurement
Cracking	Fatigue Cracking Block Cracking Edge Cracking Longitudinal Cracking Transverse Cracking	Square Meters Square Meters Meters Meters Meters
Patching & Potholes	Patch/Utility Patch Potholes	Number, Square Meters Number, Square Meters
Surface Deformation	Rutting Shoving	Millimeters Number, Square Meters
Surface Defects	Bleeding Polished Aggregate Raveling	Square Meters Square Meters Square Meters
Miscellaneous Distress	Lane-to-shoulder Drop off Water Bleeding and Pumping	Not Measured Number, Meters

Shahin et al. (1981) summarized the procedure for calculating PCI into seven steps shown in Figure 2.4. The deduct values are weighting factors that indicate the level to which the distresses are affecting the pavement. The deduct values and PCI calculation are performed according to ASTM D6433 (ASTM 2010c). Consequently, PCI provides an aggregated measure of several pavement-related features reflecting the current conditions of the road. In addition, the rate of deterioration throughout the network can also be decided.

PCI decision matrices play a key role in determining MR&R strategies, especially in identifying the various trigger points combined with the different treatment options. Additionally, it can be used in an effective way as part of the asset management programs for future budgeting and planning. Table 2.2 shows a sample for PCI decision matrix.

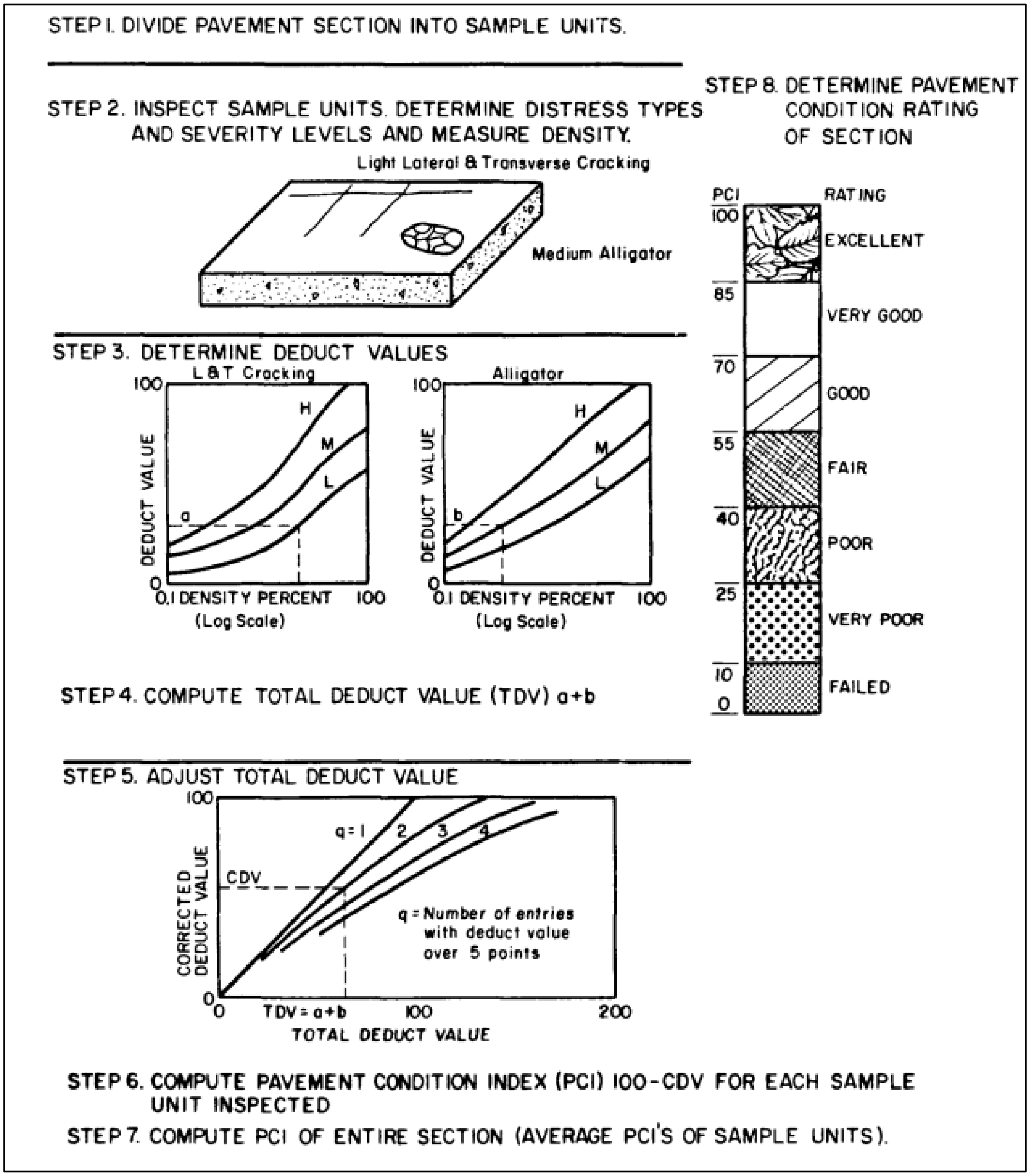


Figure 2.4 Steps for Determining PCI of a Pavement Section (Shahin and Khon, 1981)

Table 2.2 Sample of PCI Decision Matrix (Hawaii Asphalt Paving Industry, 2016)

Time of Improvement	Freeway	Arterial	Collector	Local
Adequate	>85	>85	>80	>80
6 to 10 years	76 to 85	76 to 85	71 to 80	66 to 80
1 to 5 years	66 to 75	56 to 75	51 to 70	46 to 65
Now Rehabilitate	60 to 65	50 to 55	45 to 50	40 to 45
Now Reconstruct	<60	<50	<45	<40

One of the major limitations of PCI is that it deals only with surface conditions. Regardless that surface conditions are symptoms of underlying problems, many distresses exist without any visual signs. Representing the entire pavement condition in a single point can be a crude way to evaluate the pavement. Hence, PCI should be used in conjunction with other pavement evaluation tools (Hawaii Asphalt Paving Industry, 2016).

2.4.2 International Roughness Index

Regarding quality of ride, pavement roughness is the most important factor (Carey and Irick, 1960). Haas and Haas (1979) defined pavement roughness as "distortion of ride quality." However, pavement roughness includes everything from potholes to the random deviations in road's surface (Gillespie and Sayers, 1981). Therefore, it is a result of the interaction between the surface of the road and the traveling vehicle. The ASTM E867 defines pavement roughness as, "The deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality."

Pavement roughness affects the level of serviceability a roadway provides (Hudson, 1981). Thus, pavement roughness is a major contributor to lost-load crashes. In addition, steering control capabilities and friction between the vehicle's tire and the road's surface are greatly decreased by increased pavement roughness (Burns, 1981). Moreover, higher levels of road roughness contribute to decreased roadway capacities and reduced free flow speed (FFS) (Chandra, 2004). As a result, measuring pavement roughness is a major concern for researchers and highway engineers.

IRI represents the most widely accepted index that reflects the actual pavement roughness (Sayers et al., 1986). The following subsection summarizes the efforts related to measuring roads roughness, which led eventually to the development of IRI.

2.4.2.1 The development of International Roughness Index

A sliding straightedge (Viagraph) was one of the first fundamental instruments to measure roughness (Gillespie, 1992). Due to the difficulty in moving this device, the rolling straightedge device was developed. The rolling straightedge method continued to develop with improvements in the rolling concept. An array of wheels was added to form a reference plane to measure the deviations in the road surface. This type of device represents the early stages of what is now known as profilograph.

In the 1920s, a vehicle's vibrations caused by road surface irregularities became a major concern of highway engineers in identifying a road's roughness. This led to the development of response-type road roughness meters (RTRRMs). These devices measure vertical displacements in a vehicle's rear axle. One of the major drawbacks of RTRRMs is they are highly affected by the performance (particularly the suspension) of the vehicle used in the measuring process. Regardless of the different roughness devices developed, none of these devices were able to provide a consistent measurement that could be standardized to a common scale. As a result, RTRRM measurements were not considered valid for many of the engineering applications (Gillespie, 1992).

In 1982, the World Bank sponsored a research experiment to establish a standard roughness measurement. This research effort resulted in the development of the International Roughness Index (IRI). The IRI is determined by measuring the actual road profile, and processing it through a mathematical algorithm. This algorithm, known as the quarter car simulation, simulates the response of a reference vehicle traveling at 80 km/h (49.7 mph) to road roughness (Gillespie, 1992). The accumulated suspension deflections of the reference vehicle can be divided on the traveling distance to provide an index in the units of slope (Shafizadeh and Mannering, 2002). Figure 2-5 shows the components of the quarter car simulation model (body diagram). Notice only one corner of the vehicle is simulated by sprung (ms) and unsprung (mu) masses. The vehicle tire is simulated by a linear spring of stiffness (Kt). The suspension system is represented by another linear spring with a stiffness (Ks) and a linear damper with specified damping rate (Cs).

After applying Newton's second law on the previously shown free-body diagram, considering constant traveling speed of 80 km/h and eliminating the masses, the IRI can be given through Equation 2.1 (Sayers, et al., 1986) (Du, et al., 2014):

$$IRI = \frac{1}{L} \int_0^L | Z_s - Z_u | \, dx \qquad (2.1)$$

where:
L: the measured distance along the road.
Zs and Zu: the vertical displacements of ms and mu, respectively as shown in Figure 2.5.

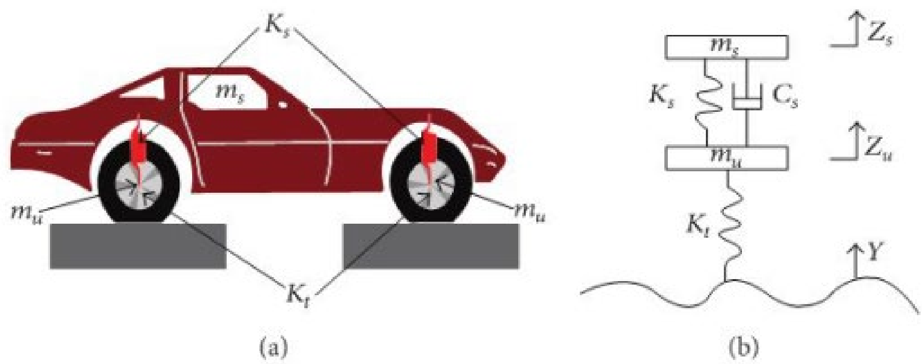


Figure 2.5 Quarter Car Simulation Components (Du, et al., 2014)

Accordingly, IRI is considered a geometric property of the road. Hence, it is a time-stable index that generates the same values when applied to the same road (Sayers, et al., 1998). WYDOT categorizes pavement ride quality according to IRI into five different groups as shown in Table 2.3.

Table 2.3 Pavement Ride Quality Based on IRI (Huntington, et al. 2013)

IRI (Inch/Mile)	Description
Less than 70	Excellent
70-100	Good
101-130	Fair
131-170	Poor
Greater than 170	Very Poor

2.4.2.2 Current Roughness Measurement Systems

The most modern roughness measurement devices are the noncontact profile measuring systems (Pavement Interactive, 2016) (Islam et al., 2014). These devices measure the deviations in a longitudinal pavement profile using acoustic or light probes. These measured profiles are then processed through computer software to calculate the IRI. One of the most popular devices of this type is the South Dakota Profiler, which uses two laser sensors to measure the road profile at both wheel paths. The measured IRI is the average IRI of both wheel paths.

In general, modern inertial profilometers measure road roughness based on four integrated basic sub-systems (Woodstrom, 1990). These subs-systems are as follows:

1. Accelerometers to measure the vertical deviations in the road profile.
2. Height sensors to measure the riding height of the vehicle relative to a location on the road being measured.
3. Distance or speed sensor (i.e., GPS).
4. Computer hardware and software to do direct computation of IRI.

Table 2.4 summarizes part of the different roughness measurement systems being used in the United States.

Table 2.4 Summary of Different Roughness Measurement Systems (Islam et al., 2014).

Roughness Measurement System	**Used Devices**
Calibration and construction control	Profilographs; Dipsticks; Ames Profilograph
Response type systems	Mays Ride Meters B&K accelerometers
Accelerometer based systems	Dynatest 5000; Self Calibrating Roughness Units
Noncontact profile measurement system	K.J. Law Roughness Surveyors, Laser Road Surface Testers; South Dakota Profilometers; Automatic Road Analyzers, Surface Dynamic Profilometers

2.4.3 Pavement Rutting

Rutting in pavement occurs due to the progressive consolidation or displacement of pavement layer materials (Serigos et al, 2012). Rutting can be either structural or lateral liquidity rutting. The structural rutting appears in the pavement surface when the applied loads exceed the strength of each pavement layer. However, structural rutting occurs normally in the lower asphalt layers (i.e., roadbed). The lateral liquidity rutting occurs normally during high temperature conditions, during which the shearing strength of the asphalt layers is highly reduced. Hence, the shearing forces produced by the repeated wheel loads exceed the shearing strength capacity of the asphalt layers (Liang et al., 2012). Pavement rutting leads to many safety issues, such as hydroplaning and small vehicles' handling at high speeds. In addition, it potentially reduces the ride quality (Serigos et al., 2012).

The most widely accepted index to characterize rutting is rut depth, as shown in Figure 2.6. According to the ASTM, rut depth can be defined as "the maximum measured perpendicular distance between the bottom surface of the straightedge and the contact area of the gage with the pavement surface at a specific location." (ASTM E1703/E1703M, 2015). Rut depth can be measured manually using a straight edge, as shown in Figure 2.7.

Figure 2.6 Pavement Rutting (Serigos et al., 2012)

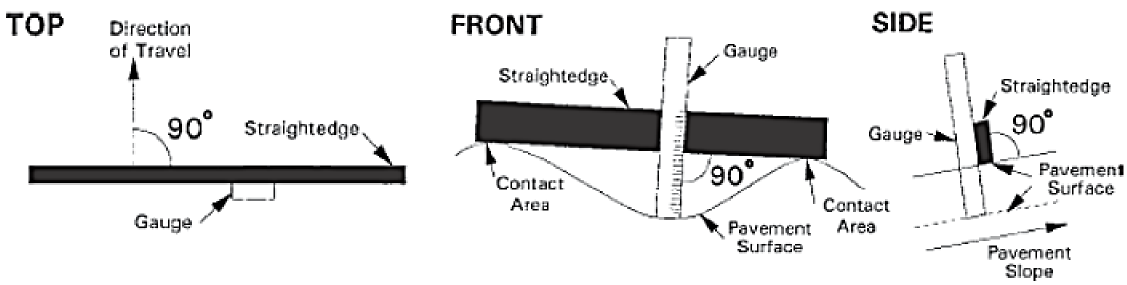


Figure 2.7 Rutting Measurement Using Straightedge Method (ASTM E1703)

In order to obtain more accurate rutting measurements, automated methods are used. Using multiple sensors, normally three to five mounted on survey vehicle, rut depth value can be calculated. Figure 2.8 shows the Pseudo-Ruts method for calculating rut depth using three sensors. Rut depth is equal to the difference between the highest and the lowest points on the measured transverse road profile (Bennett & Wang, 2002). In the five sensors case, rut depth for both wheel paths can be calculated based on the AASHTO R48-10 standard, as shown in Figure 2.9.

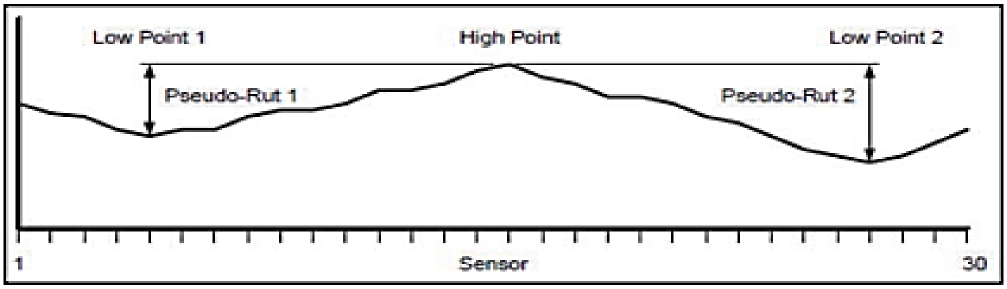


Figure 2.8 Pseudo-Ruts (Bennett & Wang, 2002)

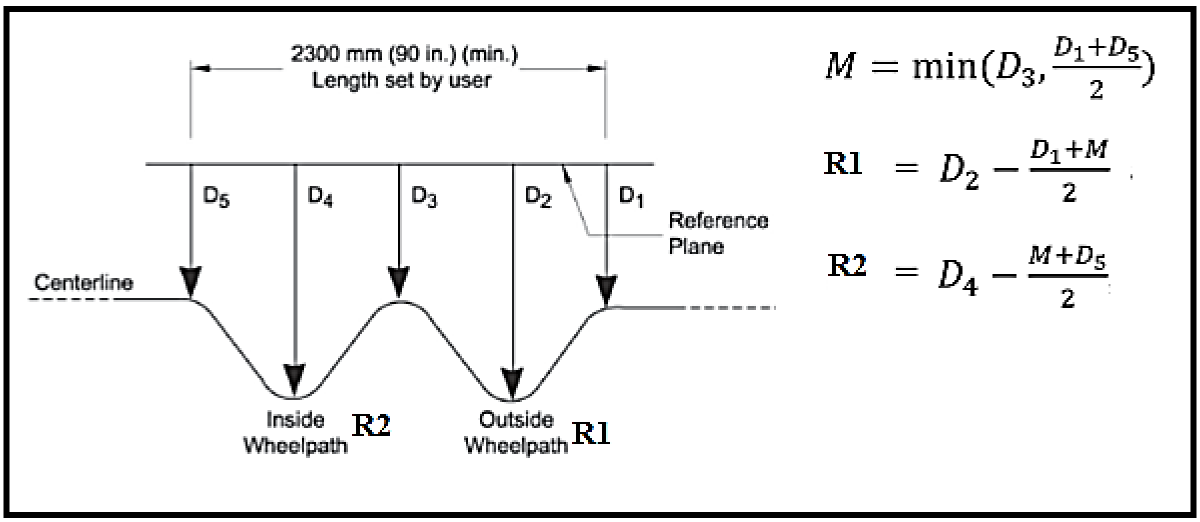


Figure 2.9 AASHTO R48-10 Method for Estimating Rut Depth, adapted from (Serigos et al., 2012)

2.5 Pavement Serviceability Concept

The purpose of any roadway is to serve the traveling public in a convenient, safe, rapid, and comfortable way. In 1962, Nakamura defined the serviceability of a pavement section as “the adequacy of a section of pavement in its existing condition to serve its intended use.” Roadway users are considered the primary customers of any infrastructure facility. Thus, their actual judgment while riding these roads is considered the main way to measure how a certain road is serving its intended use. However, this implies a subjective measure to describe the pavement performance. Moreover, it is an impractical process to collect the opinions (ratings) of roadway users regarding how they feel about riding a certain road. The human mind is very flexible, and this flexibility leaves the rating open for many personal interpretations. Therefore, many studies try to overcome the subjectivity of roadway users’ ratings by correlating these ratings to objective parameters, which are inferred from the characteristics of the actual road profile (i.e., roughness). The modern pavement serviceability concept is developed based on the following assumptions (Nair et al., 1985):

1. The driving public is the primary customer for roadways. Thus, roadways should incorporate their safety and comfort.
2. The ratings given by the driving public are subjective and highly affected by the rater’s judgment.
3. The mean panel ratings (MPR) related to a specific roadway are considered the actual serviceability of that roadway.
4. Objective parameters inferred from a roadway profile can be correlated to the subjective ratings.

5. The assessment of the driving public is assumed to be a reflection of the actual performance of the roadway.

The first major attempt to find a relation between a pavement's profile and different roadway user's perceptions was conducted by the American Association of State Highway Officials (AASHO) in 1960 (Carey and Irick, 1960). A panel of 100 individuals rated different sections on a scale from 0 to 5. These ratings are used to develop two models (one for asphaltic concrete and the other for Portland cement). The developed models correlated the different physical measurements with the panel ratings.

The AASHO research effort led to the concept of pavement serviceability. The actual mean panel ratings are considered the present serviceability rating (PSR). The predicted values of PSR through statistical models are considered as the present serviceability index (PSI) (Carey and Irick 1960). Equations 2.2 and 2.3 show the developed models in the AASHO research for flexible and rigid pavement, respectively.

$$PSI = 5.03 - 1.91\log(1 + \overline{SV}) - 1.38\overline{RD}^2 - 0.01\sqrt{C + P} \tag{2.2}$$

$$PSI = 5.41 - 1.78\log(1 + \overline{SV}) - 0.09\sqrt{C + P} \tag{2.3}$$

where:

$\overline{SV}$: Average slope variance on both wheel paths as obtained by the AASH0 profilometer.
$\overline{RD}$: Average rut depth of both wheel paths in inches.
C: Major cracking in feet per 1,000 square feet of pavement area.
P: Bituminous patching in square feet per 1,000 square feet of pavement area.

The results from the AASHO test showed that roughness was the major contributor to nearly 95% of the obtained ratings (Nair & Hudson, 1986). After the AASHO road test, several studies were performed using different devices to measure road roughness (Carey and Irick, 1960; Nakamura, 1962; Nair et al., 1985). For example, in 1962, an inclusive study was performed by Velma Nakamura in the state of Louisiana. The scope of this study included 60 pavement sections that varied between rigid and flexible pavements. The road roughness was measured using the Indiana State Highway Roughometer. Thirty raters with diverse backgrounds were requested to drive vehicles similar to their own vehicles on the selected sections and to provide their rating regarding the ride quality only. Different models with high correlation were developed using the analysis of variance (ANOVA) and linear regression that related the PSR to the measured roughness. It is concluded that the rating panel method of evaluating pavement serviceability is practical and applicable for rigid, overlay, and flexible pavements. Also, variations of knowledge and experience in the highway engineering field are not important when selecting members for rating panels.

Nair et al. (1985) conducted a ride quality experiment to incorporate the changing trends in passenger vehicles and public opinions about ride quality of Texas highways. Twenty panel members were selected to rate 171 sections (flexible and rigid pavements) using five vehicles (two subcompact cars and three midsize cars). The road roughness was measured using three different roughometers: Mays Ride Meter, SIO meter and 690D Surface Dynamic Profiler. It was found that surface roughness, vehicle size, vehicle type, vehicle wheelbase length, rater fatigue, pavement type, and maintenance were significant to the rating process. It was contradictory to the expectation that vehicle speed has no effect on the rating process.

In 1982, the World Bank sponsored research experiment that resulted in the development of IRI. As a result, there were significant research attempts to develop relationships between IRI and PSR (Al Omari and Darter, 1994; Gulen et al., 1994; Pologruto, 1999; Shafizadeh and Mannering, 2002; Hernán de

Solminihac, 2003). Al Omari and Darter (1994) performed a study on 378 sections of different types from six different states: Indiana, Louisiana, Michigan, New Mexico, New Jersey, and Ohio. They developed nonlinear relationships with reasonable R^2 values. However, the developed models are biased and invalid statistically. This is because they were forced to pass through PSI=5 when IRI is zero (Gulen et al., 1994). In the same year, Gulen et al. (1994) conducted a study in the State of Indiana. Twenty sections (9 bituminous and 11 concrete) were rated by 10 randomly chosen raters. Twenty-one different prediction models were developed for bituminous, concrete, or both pavement types. Equation 2.4 shows the model developed by Al-Omari and Darter for flexible pavements only.

$$PSI = 5e^{-0.0038.IRI} \tag{2.4}$$

where:
IRI in inches per miles.

2.6 Pavement Management Models for Local Agencies

Currently, all state DOTs have their own PMSs. As local roads are different from many perspectives compared with state highways, most state DOTs do not include local roads in their PMSs. A state-specific PMS for county roads needs to be developed considering local factors, including specific pavement deterioration models, maintenance decision trees, and optimization constraints (Wolters et al., 2011). Many agencies are presently working on developing PMS for their county roads. Note that previous studies developed models without considering the particularity of the local roads. Moreover, there are major differences between state and local roadway systems when it comes to the expectation of serviceability. These differences are crucial to develop a specific PMS for managing county and local roads. As a result, different studies have introduced a simple, effective, and affordable PMS for local agencies and municipalities, as described in the following subsections.

2.6.1 Pavement Management System for Alabama's County Roads

Although the Alabama Department of Transportation (ALDOT) has established a PMS for federal interstates and state highways, there was no PMS established for county roads statewide (Anderson & Wilson, 2005). The University of Alabama in Huntsville conducted a study to develop a procedure of data collection and analysis for county roads in Alabama. Because of the high cost and time-consuming nature of detailed pavement data collection, the rapid data collection technique is in increasing demand among highway agencies within limited PMS budgets (Bandara and Gunaratne, 2001). As a result, the University of Alabama in Huntsville designed PMS software. The software analyzes the condition data using a linear regression analysis to build a pavement deterioration model. The pavement condition was evaluated based on visual inspection rating (VSR). This rating, developed by the University of Wisconsin-Madison, is the Pavement Surface Evaluation and Rating Manual (PASER) (Walker et al., 2002). PASER is determined based on comparing standard pictures and explanations of road surfaces with the road being evaluated. The road is ranked from one to ten, with one being the worst condition, and ten being the best condition of the pavement, as shown in Figure 2.10. PASER is suitable rating for county and local roads since it is a cheap and easy procedure to evaluate the pavement condition. There is no need to use automated equipment or perform condition analyses to get the overall condition of roads.

Figure 2.10 Photographs from PASER Manual (Walker et al., 2002)

The pavement management data of county roads in Alabama were collected and analyzed using linear regression models. These models provided a moderately accurate equation used to predict the VSR for the county paved roads statewide. The VSR was predicted based on three independent variables: 1) Average daily traffic (ADT), 2) percentage of trucks, and 3) the length of time in years since the road was resurfaced. Based on correlation tests and stepwise regression analyses, the model was validated scientifically and Equation 2.6 was developed.

$$VSR = 11.2 - 0.0911 \, log \, (ADT) - 1.76 \, log \, (Years) - 0.0711 \, \% \, Trucks \quad (2.6)$$

By using the inputs and predicting models, the program can provide outputs and answers graphically. The software can provide defensible information important in the decision making process. Therefore, this study provided a simple procedure in managing county roads in Alabama. The road condition is evaluated subjectively using PASER system. Using friendly software, more detailed information about the county roads can be provided. That would enable Alabama's county engineers to make better management decisions for maintaining county roads.

However, using PASER is not the most appropriate system for evaluating Wyoming county roads. Wyoming Technology Transfer Center/Local Technical Assistance Program (WYT^2/LTAP) evaluates the overall condition of paved county roads in terms of PSI. Statewide, the decision making process depends on PSI for investing funds and for allocating appropriate treatments on Wyoming roadway networks. Therefore, using the PASER system for evaluating Wyoming county paved roads will lead to different practices and tools for local agencies, resulting in inconsistent data statewide. Consequently, it may corrupt a network-level decision making process (White, 2012).

2.6.2 Pavement Preservation of Local Roads in Washington State

The Washington Department of Transportation (WSDOT) conducted a study defining local practices for inclusion in the PMS for managing local roads (White, 2012). Two different online surveys were conducted to define different practices and current implementation within Washington state agencies. The first was the MRSC Pavement/Maintenance Program Survey created by the Washington Municipal Research and Services Center (MRSC). The second survey was the WSDOT Preservation Survey (WPS). The survey results showed a wide variety of data collection practices, which are used to evaluate pavement conditions within the state. As a result, statewide data were found to be inconsistent, which may corrupt network-level decision making. Thus, the study has recommended tools and equipment from the pavement management catalog provided by the Federal Highway Administration (FHWA) (Rohan, Pulipaka, and Kohn, 2008).

2.6.3 Pavement Management System of Local agencies in Illinois

The Illinois Department of Transportation (IDOT) developed a PMS for managing local road following these steps: 1) define the roadway network and collect inventory data, (2) collect condition data, (3) predict condition, (4) select treatments, (5) report results, (6) select pavement management tool, and (7) keep the process current. The objective was to develop a guide in implementing PMSs for local agencies. In Illinois, the pavement condition is evaluated by different condition rating systems (Wolters et al., 2011). As in Stark County, pavement condition was evaluated using the modified Pavement Condition Rating (PCR) developed by the Ohio Department of Transportation (Saraf, 1998). The PCR starts at the best condition with a value of 100; it is then reduced by deducting values based on the type, severity, and extent of pavement distresses.

2.7 Optimization Methodology for PMS

Identification of the best mix of pavement preservation projects within limited budgets was considered an important element of PMS. In order to identify the best mix of pavement preservation projects, there are common approaches such as project prioritization, project ranking, and optimization techniques (Huntington et al., 2013; Mishra et al., 2015; Saha & Ksaibati, 2015; Murillo-Hoyoset al., 2015; Mishra & Khasnabis, 2011; Mishra, 2013; Haas & Bekhor, 2017; Bačkalić, Jovanović & Bačkalić, 2015). Recently, optimization techniques have been considered the most efficient way to identify the best mix of pavement preservation projects. Optimization techniques are commonly used for resource allocation in operations research, transportation, management, finance, and manufacturing. In transportation, optimization techniques have been applied in PMS (Saha & Ksaibati, 2015; Mishra et al., 2015). In PMS, optimization methodology might involve treating roads with high traffic and maximizing the weighted average PSI based on a set of decision variables subject to various constraints such as budget. Different optimization techniques, such as linear, integer, and dynamic programming, were implemented in previous studies (Mishra et al., 2015). Optimization techniques in PMS include application of both linear and integer programming.

2.7.1 Linear Programming

Linear programming is set in optimization models when objective and all constraint functions have linear relationships. The standard formulation of this problem is introduced in Equation 2.7. The transposed (*T*) matrices of vectors c, $a_1, a_2, \ldots, a_m$ are the problem parameters, whereas $b_1, \ldots, b_m$ should be scalars of defined constraints. In this analysis, the decision variable *x* is optimized linearly to end up with only one feasible solution. Thus, objective and constraints functions should form a convex plane feasible solution region (Bertsekas, 2009).

$$\begin{aligned} &\text{minimize} \quad c^T x \\ &\text{subject to} \quad a_i^T x \le b_i, \qquad i = 1, \ldots, m. \\ &\qquad\qquad\quad x \ge 0 \end{aligned} \tag{2.7}$$

Over many decades, linear programming has been employed in the optimization analysis of pavement maintenance. In Arizona, Golabi et al. (1982) developed a linear-programming optimization model for the objective of maintenance planning and budget allocation in Arizona DOT's (ADOT) PMS. The results of the four-year study provided considerable savings. The same basic formulation of this study has been adopted in a number of state PMSs, such as Alaska, Kansas, and Portugal (Alviti et al., 1994; Golabi, 2002). Grivas et al. (1993) integrated engineering factors with the economic analysis to provide effective optimization models using linear programing. Theodorakopoulos et al. (2002) developed a linear programming tool to optimize the network-level agency costs subjected to desirable pavement condition constraints. Optimal maintenance strategies were proposed to help decision makers consider relevant project-level maintenance and rehabilitation (M&R) decisions. De La Garza et al. (2011) optimized a case study of paved roads in Virginia DOT (VDOT) using the linear programming of *Solver* add-in for Microsoft Excel.

2.7.2 Integer Programming

Since some of pavement maintenance parameters are categorical, some research efforts have shifted toward the use of integer programming techniques. The integer analysis is combined with the linear programming by adding the constraint (x_j integer for $j = 1, 2, \ldots, n$). This problem is called integer linear programming, in which the objective function and the constraints, other than the integer constraints, are linear.

Chen et al. (1992) used a mixed-integer programming model to minimize the total cost of pavement structures while meeting the constraints of AASHTO flexible pavement design criteria. The integer inputs of this problem represent the categorical type of paving materials while the non-integer variable is the pavement thickness. The binary variable of pavement maintenance decision making was introduced by Li et al. (1998). In this study, a multi-year optimization technique was developed for pavement preservation of the road network under the constraints of annual budget limitations. The results showed robust means of solving pavement management optimization problems.

2.8 Roughness Measurement Using Smartphones

Modern smartphones are equipped with many useful sensors, such as gyroscopes, magnetometers, GPS receivers, and 3D accelerometers. These sensors are usually used to identify the orientation of the smartphone screen and other functional activities (Douangphachanh and Oneyama, 2013). A 3D accelerometer is a sensor that measures the changes in velocity among the X, Y, and Z axes in the units of acceleration (m/s^2). Several studies were performed to utilize 3D accelerometers in identifying roadway conditions (Strazdins et al., 2011; Douangphachanh and Oneyama, 2013; Jiménez and Matout, 2014; Hanson et al., 2014).

Strazdins et al. (2011) performed a study using three android smartphones to detect potholes and bumps that exist on roadway surfaces. Despite the low accuracy of the GPS receivers and 3D accelerometers, they found by using simple algorithms the detection of potholes and bumps was possible using smartphones.

In Vientiane, the capital of Laos, Douangphachanh and Oneyama (2013) conducted a study in a trial to estimate IRI through smartphones' accelerometer measurements. They used two android smartphones (*Samsung® Galaxy Note* II and III) mounted on the dashboard of the test vehicle. Two vehicles, a Toyota VIGO 4WD pickup truck and a Toyota Camry, were used in this experiment. The IRI was measured using a vehicle intelligent monitoring system (VIMS) for every 100m. A fast Fourier transform (FFT) was performed on the accelerometer data to obtain a frequency domain view of each signal. A linear relationship was found between the sum of magnitudes from FFT and the measured IRI. The established relationship was statistically significant when the speed was less than 60 km/h (37.3 mph), with a partial dependence on the vehicle and smartphone types. One year later, Jiménez and Matout (2014) used a tablet's built-in accelerometers to assess the pavement roughness. It was found that the standard deviation of vertical accelerations normalized by the driving speed could give a good indication of the road roughness condition. However, this study did not develop a direct correlation to estimate the IRI. The returned response of the accelerometer was able to identify the different levels of roughness, as shown in Figure 2.11.

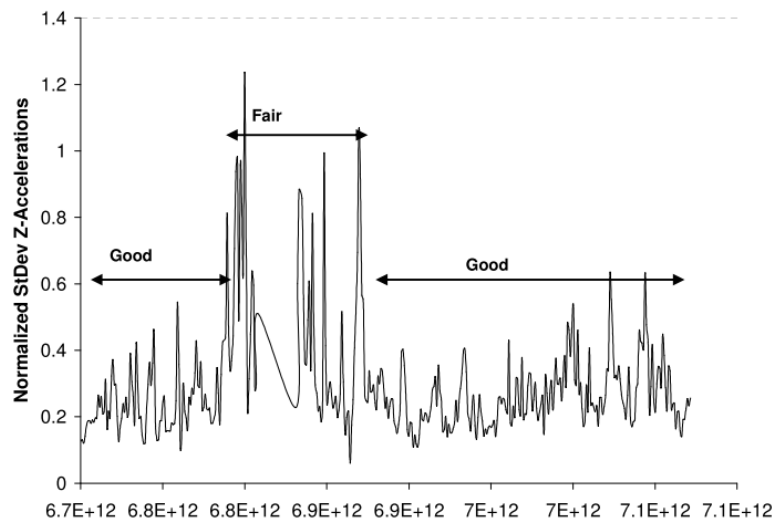


Figure 2.11 Roughness Levels Identified by the Response of Vertical Accelerometers (Jiménez and Matout 2014)

In the same year, Islam et al. (2014) conducted a study at the University of Illinois to determine the IRI using a smartphone's integrated accelerometers. Three test sites (each two miles long) with various roughness conditions were selected. By using a double integration method on the vertical acceleration data obtained by the smartphones, a perceived road profile was formed. The perceived road profile was converted to IRI using ProVAL software (Profile Viewing and Analysis Software). It was found that the calculated IRI values were in good agreement with the measured IRI values using a standard inertial profiler. However, calibration was required for rougher pavement sections to overcome the effect of suspension damping. This methodology was first adapted by Hanson and Cameron (2012) at the University of New Brunswick, Canada. However, Hanson and Cameron used DATS Toolbox software to convert the acceleration data to displacement. The DATS Toolbox software divided the FFT of the acceleration data by the negative angular frequency of the signal's components squared to get the displacement. This process helped avoid the accumulation of errors that result from using numerical integration (i.e., cumtrapz integration).

The previous studies have proven the smartphone's ability to collect IRI data. However, these studies were limited to measuring IRI at low resolutions (i.e., 100m or 0.1 mile sub-segments) with limited changes in horizontal and vertical alignments. Moreover, high pass filters or low pass filters were used to filter the accelerometer data. These filters use certain cut-off frequencies, which greatly affect the final calculated IRI values. Nevertheless, smartphones appear to be a promising tool in minimizing data collection costs, especially at the local level.

2.9 Chapter Summary

This chapter provided an overview of a pavement management system (PMS) and a background of previous studies on PMSs for local agencies. Terminologies related to PMS and roadway condition indices were presented in this chapter. The methodologies related to measuring roadway condition indices were discussed with emphasis on IRI and PSI. The development of IRI was described in detail in addition to current roughness measurement systems. The optimization approach allows state DOTs to develop cost-effectiveness maintenance plans with respect to available maintenance resources and budget levels. Three mathematical methods are commonly applied in optimization analysis of generic pavement maintenance planning: linear programming, integer programming, and dynamic programming. They provide robust techniques; however; complex mathematical formulation is considered in the optimization models. When it comes to managing county roads, limited optimization applications are found within local management systems. In addition, several attempts to measure IRI using smartphones were covered. The previous studies have proven the smartphone's ability to collect IRI data. However, these studies were limited to measuring IRI at low resolutions.

3. METHODOLOGY

This chapter introduces the overall research methodology, as shown in Figure 3.1. The first step is to build a comprehensive database of pavement management data collected as part of the Wyoming county roads PMS building process (Saha and Ksaibati, 2015b). Pavement serviceability prediction models and optimization models are formulated considering the pavement condition parameters of Wyoming's county paved roads. In addition, different methods are also presented to evaluate the effectiveness of smart phones in measuring county road roughness as a cost-effective solution in Wyoming. A model development process was divided into multiple steps. These steps are described in the following subsections.

3.1 Building a Comprehensive Distresses Database

Experiments performed in this study depended on data extracted from Wyoming county roads PMS database. This database was developed in 2014 as WYDOT contracted with Pathway Services Inc. to collect pavement condition data biannually. Pathway Services Inc. provided automated data collection vehicles equipped with sensors, video cameras, and computers, as shown in Figure 3.2. Pathway Services vehicles traveled on county roads providing data about the actual road profile. These data included direct measurements of IRI and rut and video logs of the surface distresses. The WYT^2 /LTAP center analyzed and combined these data in a single database (Huntington et al., 2013). Figure 3.3 summarizes the roadway condition indices collection process. The process of data collection is described in the following subsections.

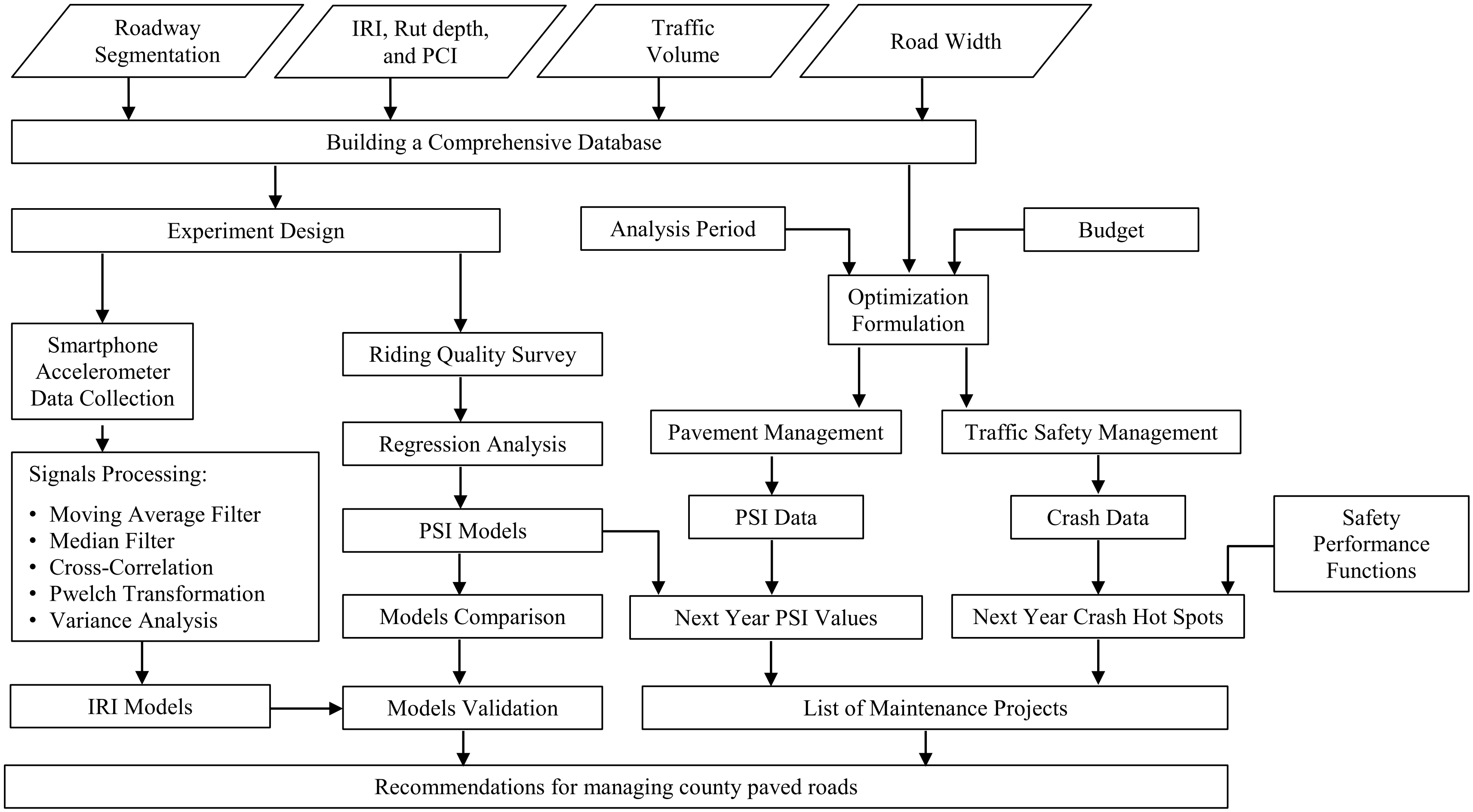


Figure 3.1 Overall Research Outline

Figure 3.2 Pathway Services Van (Pathway Services Inc, 2016)

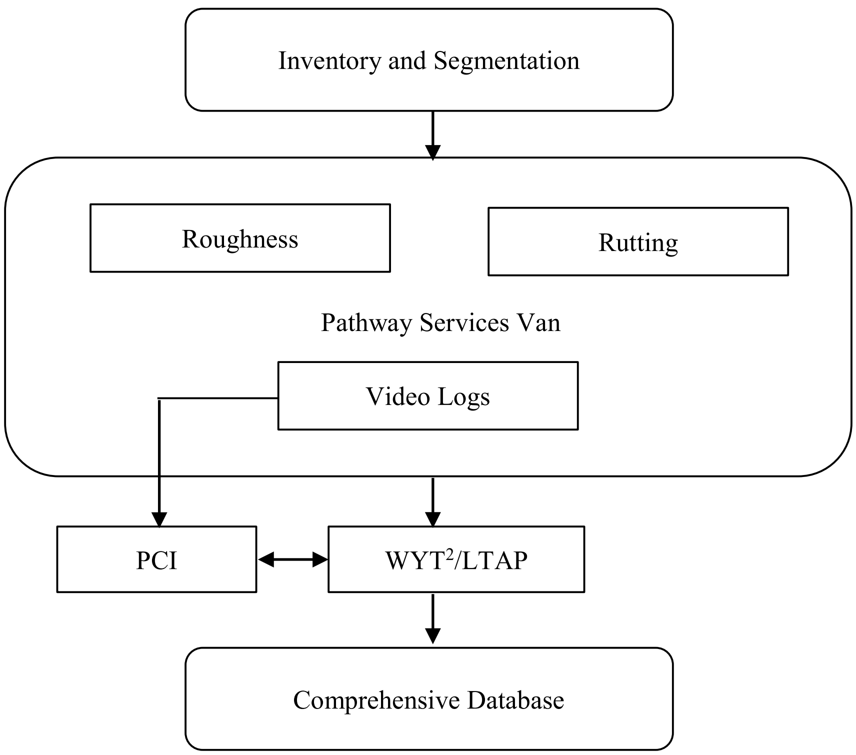
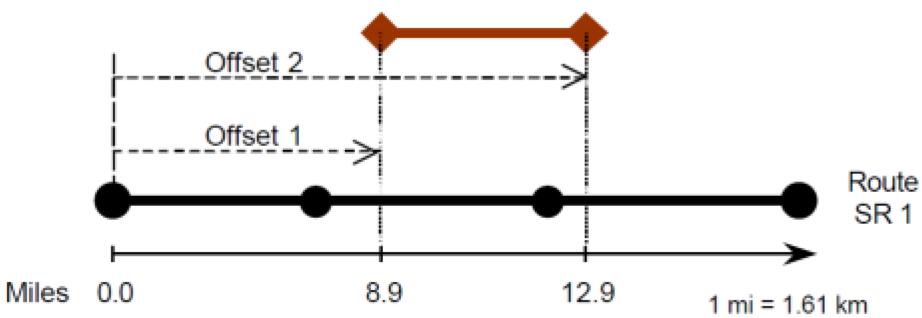


Figure 3.3 Schematic Diagram for the Data Collection Process

3.1.1 Segmentation

Since PMS relies on data from a variety of resources, the collected data must be summarized based on homogenous properties. This facilitates the accessibility and the management process of these data. Applying network segmentation divides the roadway network into consistent and smaller uniform parts (Pierce et al., 2013). Later, these parts or segments were used in the identification process of the different maintenance and rehabilitation needs. One of the most popular segmentation methods is dynamic segmentation, where segmentation regions with statistically similar conditions are combined. In other words, the trends of the collected data are controlling the segmentation process (Kennedy et al., 2000). The dynamic segmentation is different from the static segmentation, as the latter always divides the network data at specific rigid boundaries. In certain locations where maintenance records are limited or PMSs are being newly established, segmentation can be performed based on changes in surface type, construction boundaries, usage levels, and intersections. For example, construction boundaries and intersections are the major factors in the segmentation process of county roads in Wyoming.

In order to refer to the segmented parts of the network, a location referencing system (LRS) is used. The LRS provides the ability to link the roadway condition data to geographic locations in visual display means. This presentation of data is very important, especially in regard to the analysis and reporting processes. The LRS used in Wyoming county roads identifies a specific location by assigning the roadway segment a unique name or value (i.e., ML1102B). The exact location is then expressed by combining that unique name with the traveled distance from a referenced station (RS). Figure 3.4 shows a sample for identifying a specific segment (in red) on route SR1 using mile posts from a referenced station (0.0).



Surface Condition Database

Route	Begin MP	End MP	Condition
SR1	8.9	12.9	Good

Figure 3.4 Route-mile (km) Posts Sample (Pierce et al., 2013)

3.1.2 International Roughness Index (IRI)

The IRI is measured using the South Dakota profiler. This device is a laser type profiler manufactured according to ASTM E950 specifications and meets class 1 requirements (Pathway Services Inc. 2016). The longitudinal pavement profile for both wheel paths was measured and analyzed using the quarter car simulation to generate the actual IRI value. The average IRI of the right and the left wheel paths was considered the final IRI.

3.1.3 Pavement Condition Index (PCI)

A distress survey was required to obtain the PCI values. In the county roads case, video logs representing the real road surface were provided by Pathway Services Inc. For every mile of roadway segment, random 1,000-ft. sub-segments were surveyed using these video logs (Huntington et al., 2013). The purpose of using sub-segments was minimizing the efforts required to survey the entire network (Shahin, 1994). The Software provided by Pathway Services Inc. was used to run these video logs. This software provides a real-time display of the road surface, as shown in Figure 3.5, to identify the pavement cracking visually. All types of cracks are compromised in the software to automatically determine the PCI deduct values. The average PCI of all sub-segments was considered the final PCI for the entire roadway segment. Video log processing, data analyzing, and summarizing were conducted by WYT^{2}/LTAP.

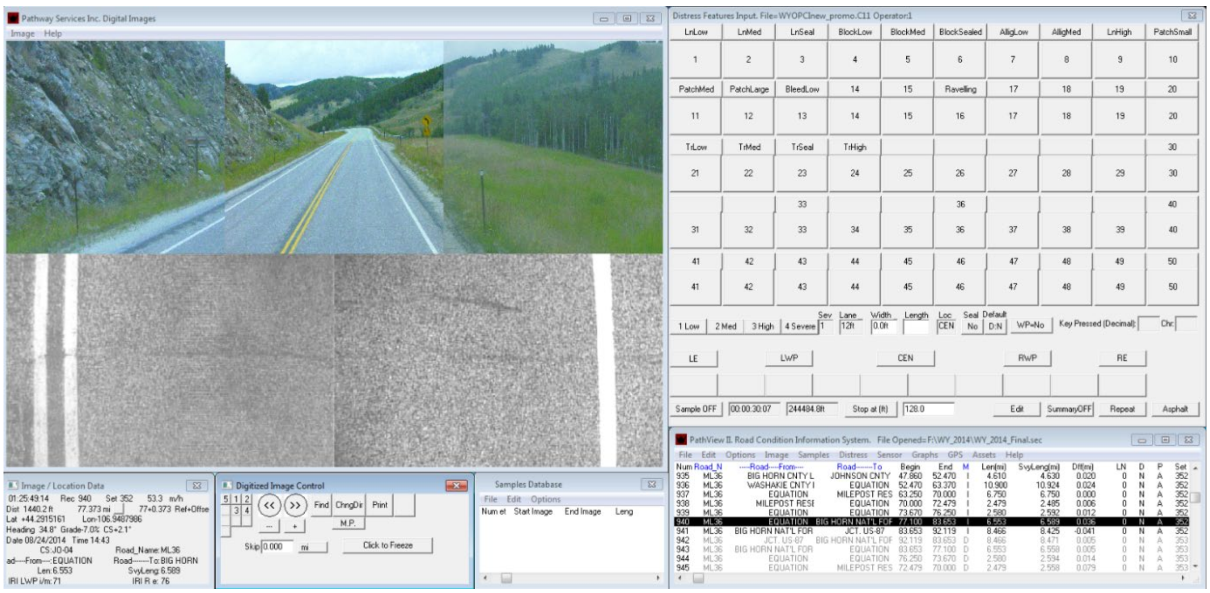


Figure 3.5 A Screen Shoot for a Video Log Played by Pathway Services Software (Hafez, 2015)

3.1.4 Rut depth

Transverse profile data were collected as part of the *PathRunner* Data Collection system. In the *PathRunner* system, 1,500 data points were collected per transverse profile. However, the transverse profiles were measured at every one-inch interval spacing at the network level. This interval can be adjusted based on the different uses (i.e., project level). Every 12 transverse profiles were averaged in order to produce a single transverse profile. Using computer software, this perceived profile was filtered and processed using different algorithms to provide the final rutting values (Serigos et al., 2015; Huntington et al., 2013).

3.1.5 Present Serviceability Index (PSI)

PSI provides a single number on a scale from 0 to 5 that evaluates the overall condition of the pavement from the traveling public's perspective. Equation 3.1 is used by WYDOT to calculate the PSI of the state highway system.

$$PSI = 5.35e^{-0.0058*IRI} - 4RUT^2 - 3\left(1 - \left(\frac{PCI}{100}\right)\right) \quad (3.1)$$

where:

IRI: the international roughness index (inches/mile)
RUT: the mean rut depth (inches)
PCI: the pavement condition index (based on ASTM D6433)

The following rating scale is used in this project to describe the condition of roads with a particular PSI value:

Greater than 3.5	-	Excellent Condition
3.01 – 3.5	-	Good Condition
2.51 – 3.0	-	Fair Condition
2.0 – 2.5	-	Poor Condition
Less than 2.0	-	Very Poor Condition

The analyzed distresses datasets are merged into a single comprehensive database representing the average pavement condition by segment. A comprehensive database sample is presented in Table 3.1.

Table 3.1 A Comprehensive Sample Roadway Condition Database

COUNTY	Route	BegMP*	EndMP*	Rut(in)	IRI(in/mile)	PCI	PSI
Laramie	ML1102B	0.620	2.110	0.14	128	73	1.66
Laramie	ML1102B	2.110	2.610	0.16	108	71	1.89
Laramie	ML1108B	1.354	1.499	0.15	60	100	3.69
Laramie	ML1108B	1.499	1.616	0.09	115	100	2.71

Note: BegMp = Beginning Mile Post; EndMp: Ending Mile Post

In addition, the LRS is combined with the Global Positioning System (GPS). This system simplifies the identification process by assigning certain coordinate values (i.e., longitude and latitude) to different locations. Hence, these locations can be reached easily using any GPS receiver. In addition, the GPS data can be stored into the Geographical Information System (GIS) database, which allows data integration. GIS maps can merge cartography, statistical, and condition data. Figure 3.6 shows a GIS map with pavement condition ratings of the different pavement segments in Wyoming.

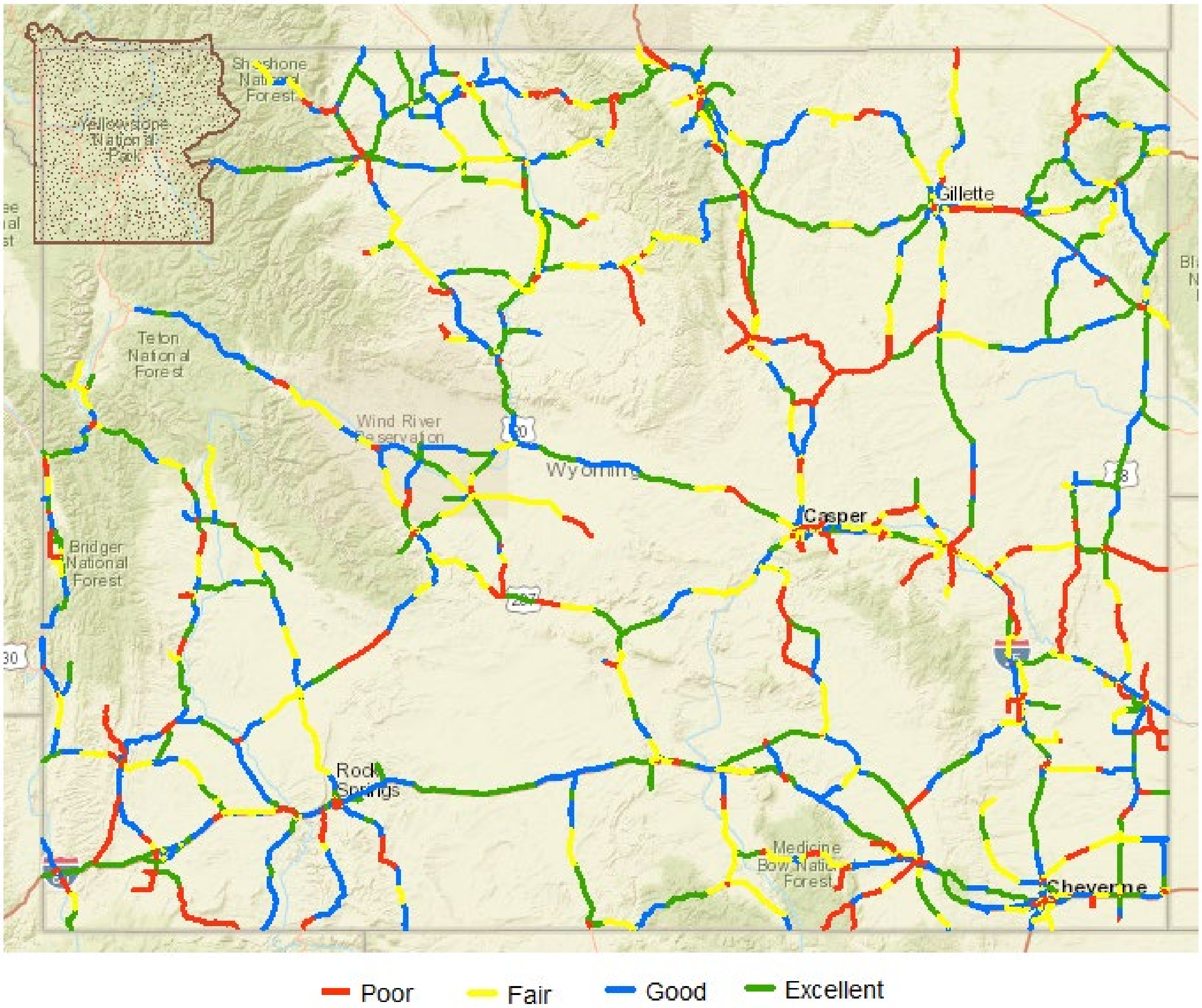


Figure 3.6 GIS Map Shows Pavement Condition Ratings in Wyoming (WYDOT, 2016)

3.2 Experiment Design

The validity or reliability of any research is highly dependent on the procedures and techniques followed during its performance. Different experimental strategies can highly affect the quality of any performed study. They can also introduce many sources of error and bias, especially in uncontrolled environments. The development of serviceability and roughness prediction models included two experiments that dealt with roadway segments as part of the Wyoming county roads PMS. These experiments were designed in a way that guarantees the validity of the outcomes up to acceptable levels. In addition, the design aimed to perform the experiments in a cost effective way within a short time. The design of these experiments is described in the following subsections.

3.2.1 Riding Quality Survey

A riding quality survey experiment was designed taking into account the particularity of the local county roads. Road sections with various roughness levels were included in the experiment. A panel representing localities in Wyoming rated selected sections using two different vehicles on a scale from 0 (worst) to 5 (best). Panel members rated the selected segments based on their comfort level only while riding over these segments. The mean panel rating (MPR) for each segment was considered the PSR for that segment. General driving styles and transport vehicle selection were very important in representing the normal driving scenario on Wyoming county roads. The riding quality survey should be conducted within the same time frame as the pavement condition data collection (ASTM E1927-98). One day prior to the rating day, raters were given detailed instructions on the riding quality survey. On the morning of the rating day, they were given a short rating session to help them build up the needed sense of feeling road roughness. The rating panel instructions and the short rating session details are shown in Appendix A-1. The experiment design was divided into three sections: (1) pavement test sections selection, (2) transport vehicles, and (3) panel selection.

3.2.1.1 Pavement Test Sections Selection

The pavement sections were selected based on homogeneous physical properties that covered a wide range of roughness. The sections were straight and long enough to maintain a fixed speed with a minimum of 25-second exposure time. Usually, the driving speed would be similar to the posted speed limit. According to the ASTM (E1927-98) procedure, a minimum number of 20 sections should be selected for each pavement type. In this study, a total of 30 flexible pavement sections were randomly selected, three at each pavement condition index level to achieve a representative random sample. Table 3.2 shows the different roadway condition indices considered in the study. The lists of the selected roadway segments for riding quality survey are shown in Appendices A-2 and A-3 for the SUV and sedan vehicles, respectively.

Table 3.2 Roadway Condition Indices Used in the Sections of Test Selection

IRI (Inch/Mile)	PCI	Rut (Inches)
Less than 70 70-100 101-130 131-170 Greater than 170	Greater than 85 70-85 Less than 70	0.3 inches or less More than 0.3 inches.

3.2.1.2 Transport Vehicles

In this study, two vehicles were selected: a sedan vehicle (2011 Ford Fusion) and SUV vehicle (2014 Ford Explorer). The four-wheel-drive (4WD) SUV vehicle was selected since the majority of Wyoming drivers tend to use this type of vehicle due to the statewide severe snowy weather conditions. Figure 3.7 shows the vehicles selected to perform the rating process.

Figure 3.7 Selected Vehicles for the Riding Quality Survey

3.2.1.3 Panel Selection

The panel size was selected based on the maximum allowed error criteria defined by ASTM, as shown in Table 3.3. The panel size was defined to be 10 based on 0.4 MPR maximum error with normal distribution for the SUV vehicle and six based on 0.5 MPR for the sedan vehicle. The potential panelists were requested to complete a panel selection form, which was meant to gather useful information about the panelists and their driving styles. This form is shown in Figure 3.8. The panelists were chosen from different backgrounds as shown below:

- Four panelists: one woman and three men selected from the Wyoming T²/LTAP center with an average age of 44 years.
- Three panelists: one woman and two men selected from the civil engineering graduate department of the University of Wyoming with an average age of 24 years.
- Three panelists: three men selected from the WYDOT Design Squad with an average age of 22 years.

Table 3.3 Panel Size as a Function of Error

Error (MPR Units)	Non-Normal Distribution	Normal distribution
0.1	319	138
0.2	80	35
0.3	36	15
0.4	20	9
0.5	13	6
0.6	9	4
0.7	7	3
0.8	5	-
0.9	4	-
1.0	3	-

University Of Wyoming
Civil & Architectural Engineering Department

Riding Quality Study
Summer 2015

Panel Selection Form

(1) Name:…………………………………………………………………………………………....

(2) Phone No……...…………………… Appropriate time for calling you ……………...............

(3) Current Work Description ………………………………………………………………………

(4) Sex : ☐ Male ☐ Female,Age ……………yrs.

(5) How many years have you been a resident of Wyoming (or surrounding areas/ mention current address)?

Use the following table for the next two questions:

(6) What car(s) do you drive (or ride in)?

(7) Of the time that you are on the road, approximately how much of the time do you drive or ride in each of these cars daily?

Year/Make/Model	Drive	Ride	Approx.Duration

(8) On an average, how many miles per year do you travel on the road?

----

(9) which of the following best describes your attitude towards road travel in general? (Circle your answer)

(a) Highly enjoyable

(b) Fairly enjoyable

(c) Indifferent

(d) Cumbersome

Figure 3.8 Panel Selection Form, Adapted from (Nair, Hudson, & Lee, 1985)

3.2.2 Determining IRI Using Smartphones

This part of the study was based on the idea that roads with similar conditions may provide similar signal patterns (time series acceleration data) using smartphone accelerometers. In other words, smartphone accelerometers were used to capture the vertical vibrations while driving the testing vehicles. Different analysis techniques were performed to find the key features among the acquired acceleration signals. Hence, the signals produced by the accelerometer can be considered a reflection of the actual road profile. Different roadway segments with various roughness levels were selected to perform this part of the study. Then using a sedan vehicle with smartphones fixed on its dashboard, accelerometer data were collected over these segments.

Since the smartphones were fixed horizontally (i.e., in X and Y), the variations along the Z axis were the focus of this study. Therefore, the time series vertical acceleration data formed a signal that represents the vibrations of the testing vehicle, reflecting actual road roughness.

Both median and simple moving average filters were applied to reduce the amount of noise in the accelerometer signals (Mitra, 2011). The median filter is a nonlinear digital filter that replaces the neighboring entries of a signal by the median of these entries. The pattern of the neighboring entries is identified by a window that slides over the entire signal. Using this filter helped eliminate the variations that might result from unusual surface anomalies (i.e., potholes, manholes), which can be considered statistical outliers. The moving average filter is a digital filter that replaces the neighboring entries of a signal by the average of these entries. This results in reducing the short-term fluctuations and highlighting the longer-term trends in the signal. For this study, the acceleration data were filtered first by applying a median filter with a window size of 5. The accelerometer data were then filtered again using the moving average filter with a window size of 10. This signal conditioning was accomplished off-line as a post-processing procedure.

Different pattern recognition techniques were used to find similarities or key features among the measured signals in each roughness category. Specifically, cross-correlation, Welch periodogram estimates of the power spectral density (PSD) and variances among the accelerometer data were performed to recognize different signal patterns. The cross-correlation is a statistical measure of similarity between two different signals. It can be considered a sliding dot product of two data series as a function of the lag between the same two series. The cross-correlation is similar to the mathematical convolution between two functions, except that convolution requires one of the two data series to be “flipped” (i.e., reversed) in time. Autocorrelation is the same procedure as cross-correlation, except that the two signals are the same (Mitra, 2011). In signal analysis, cross-correlation yields an amplitude function in the units of lag. Figure 3.9 shows a demonstration for convolution, cross-correlation, and autocorrelation to find the point of maximum similarity between two signals, (f) and (g), as a function of lag. The lags with the highest amplitude represent the points of highest similarity.

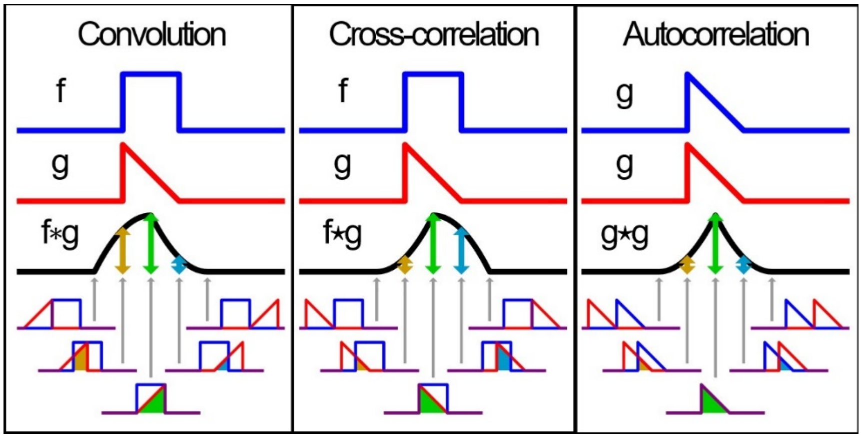


Figure 3.9 Comparison Between Convolution, Cross- Correlation and Autocorrelation, Adapted from (Cmglee [Own Work], 2016)

The Welch periodogram is a method used to estimate the power in a signal at different frequencies. This is called the power spectral density (PSD) of a signal. An estimate of the PSD was performed on every measured signal. These estimates were used to identify any unique fluctuations or features of the power among the different frequencies. These fluctuation points can be used as a way to identify the different measured signals.

Finally, variance analysis was conducted to assess the trends of the measured vertical accelerations using the smartphone accelerometers. The calculated variance was compared with the referenced IRI value for each segment. The variance among the accelerometer readings for every segment was calculated as the second central moment, according to Equation 3.21 (The Sample Variance, 2016). This is a well-known method of calculating the unbiased variance of data.

$$\mathrm{Var} = \frac{\sum_{i=1}^{n}(X_i - \bar{X})^2}{n-1} \tag{3.21}$$

where,
n: is the total number of the vertical acceleration readings for the segment
i: is one of the measured vertical acceleration readings for the segment
X: is a value for one of the vertical acceleration readings
$\bar{X}$: is the arithmetic mean of the n readings

Two smartphones, a Samsung Galaxy SIII and a Sony Xperia A, were selected to collect the vertical acceleration data. The smartphones were glued close to each other on the testing vehicle's dashboard. A 2011 Ford Fusion sedan was selected as the testing vehicle for this study. Figure 3.10 shows the testing vehicle and smartphone arrangement used in this study. Twenty roadway segments were selected from the Wyoming local county roads PMS database (Laramie and Albany counties). These segments were randomly selected to include different roughness levels. The same IRI thresholds shown in Table 3.2 were considered in this study. The selected segments covered various geometric features with different lengths reflecting the actual roadway segments under any PMS. Table 3-4 shows a summary of the statistics for the selected test segments. Notice that 65% of the selected segments have IRI values less than 210 in/mile. The other 35% of the segments have IRI values greater than 210 in/mile. This wide distribution of IRI values helps provide a realistic evaluation of smartphone sensors in measuring IRI values as part of county roads PMSs. The roadway segments used in this part of the study are shown in Appendix A-4.

Figure 3.10 Test Vehicle and Smartphones Orientation

Table 3.4 Summary of Test Segments

Number of Test Segments	Parameter	Mean	Median	Standard Deviation	Max	Min
20	IRI	151 in/mile	118 in/mile	92.3	390 in/mile	59 in/mile
	Length	1.1 miles	1.01 miles	1.1	2.96 miles	0.14 miles

3.3 Regression Analysis to Develop PSI Models

Different diagnostic analysis techniques were performed to check the normality of ratings, outliers, and homogeneity of variances among the raters. To test the normality of samples, the Shapiro-Wilk test was used. This test calculates the W-statistics, as shown in Equation 3.3, from a normal distribution or not (Anderson-Darling and Shapiro Wilk tests, 2015).

$$W = \frac{(\sum_{i=1}^{n} a_i x_{(i)})^2}{(\sum_{i=1}^{n} x_i - \bar{x})^2} \quad (3.3)$$

where,

$x_{(i)}$: is the ordered sample values (in ascending order).

a_i : are constants generated from the means, variances, and covariances of the order statistics of a sample of size *n*.

The Shapiro Wilk test tests the null hypothesis (H_o) in which “samples come from a normal distribution,” against the alternative hypothesis in which “the samples do not come from a normal distribution.” Shapiro-Wilk tables were used to define the P-value related to the calculated W-statistic. The defined P-Value should be greater than the critical P-value (i.e., 0.05) to consider the normality of the tested samples.

The Bartlett's test was used to test the homogeneity of the variances among the different raters. The analysis tests the hypothesis: H_o: $\sigma^2_1 = \sigma^2_2 = \ldots\ldots\ldots \sigma^2_9$;

where,

σ^2_n : is the rater's variance. The test calculates the T-Statistics using Equations 3.4 and 3.5 (Bartlett's test, 2015):

$$T = \frac{(N-k)lnS_p^2 - \sum_{i=1}^{k}(N_i-1)lnS_i^2}{1+(\frac{1}{3(k-1)})((\sum_{i=1}^{k} 1/(N_i-1))-1/(N-k))} \tag{3.4}$$

$$S_p^2 = \sum_{i=1}^{k} \frac{(N_i-1)S_i^2}{N-k} \tag{3.5}$$

where,

S_i^2 is the variance of the i^{th} group

N: is the sample size

k : is the number of groups

S_p^2 : is the pooled variance

The null hypothesis can be rejected and the variances will not be considered homogeneous, if the value of T> $X^2_{1-\alpha,k-1}$, where $X^2_{1-\alpha,k-1}$ is the critical value of the chi-square distribution with k - 1 degrees of freedom and significance level of α.

After conducting the diagnostic analysis, linear regression analysis with multiple predictors, including transformed variables, was used in the development of the PSI model. The predictor variables included IRI, PCI, and rut depth. The general multiple regression model used in this study is shown as Equation 3.6.

$$Y_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \beta_3 X_{i3} + \varepsilon_i \tag{3.6}$$

where,

Y_i : is the response variable that represents PSI

X_{i1}, X_{i2}, X_{i3}: are the predictor variables that represent IRI, PCI, and rut depth

$\beta_1, \beta_2, \beta_3$: are the regression coefficients

ε_i : is the random normally distributed error term

In order to investigate the performance of the developed PSI model, a comparison analysis was then conducted between the county and the WYDOT model. In addition, the developed county model was compared with a basic model developed according to the ASTM approximation of MPR values listed in Table 3.5 to confirm its validity.

Table 3.5 ASTM Approximation of MPR from IRI Measurements

IRI Measurement (in/mile)	**Approximate MPR**
25	4.5
50	4.0
75	3.5
125	3.0
200	2.5
300	2.0
500	1.5
800	1.0

3.4 Optimization Methodology for PMS

This section presents the formulation of the risk-based pavement optimization used in the pavement management model. The primary variable of this model is the PSI, which was discussed earlier. Depending on the PSI, a decision tree is used to identify the appropriate treatment type. Next, the algorithm for identifying the best mix of preservation projects is discussed. It is important to mention that this model does not consider political factors, but purely life-cycle cost of pavements.

As shown in Figure 3.11, there are two phases to finalize the optimization model. In the first phase, a comprehensive database was developed. This database included the pavement condition parameters, traffic volume, roadway functional classification, and road width. The overall pavement condition of each segment was then calculated based on PSI models. The second phase shows the various steps involved in the optimization model. In this model, selected projects for maintenance identified for the next five years are listed. Rut depth was used in the decision tree as well as the PSI model. This is because rut depth is a very critical factor when selecting appropriate rehabilitation treatments. Also, rut depths greater than 0.3 inches are considered hazardous in Wyoming. The inclusion of rut depth in identifying treatments for county paved roads was approved by county engineers in Wyoming.

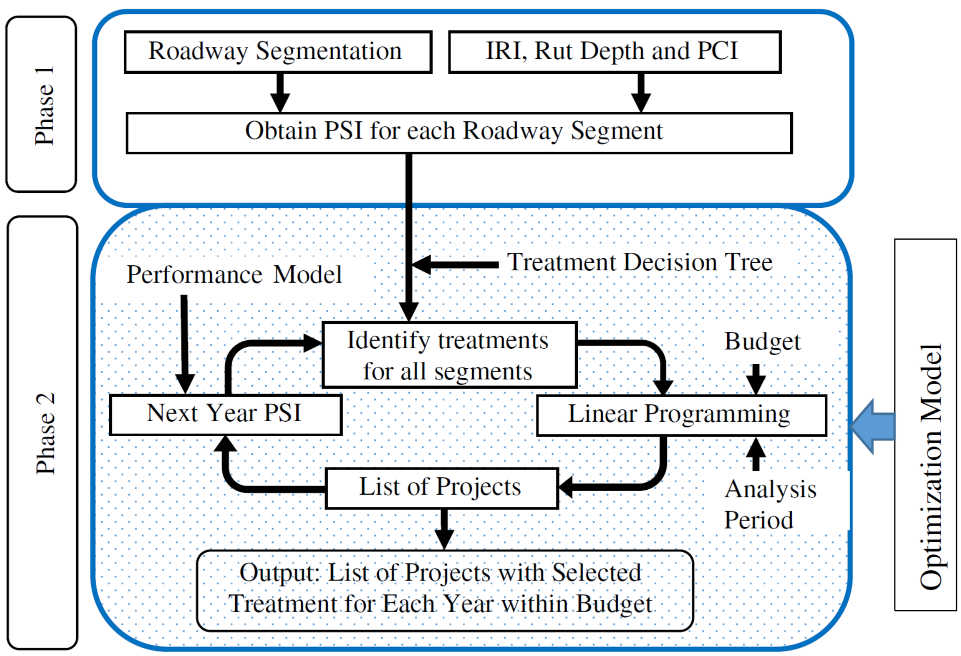


Figure 3.11 Methodology for PMS Optimization Model

3.4.1 Treatment Types

On Wyoming's county roads, there are six possible treatment options summarized in Table 3.6, along with descriptions, applications, and estimated costs per mile. In this table, notice that the estimated costs per mile for different treatment types are rounded to the nearest $10,000. From previous research, it was found that general maintenance (GM) costs range from $1,000 to $2,500 (City of Milton, 2009). Because of having very low costs associated with GM compared with other treatment types, GM is considered as zero (0) in this research. The cost of various treatments was obtained from county engineers and road superintendents in various Wyoming counties (Huntington et al., 2013).

Table 3.6 Pavement Treatment Options for County Pavement Roads

Treatment Type	Details and Applications	Estimated Cost/mile
GM General Maintenance	• General Maintenance Procedure • Asphalt Patching • Pothole Repair • Crack Sealing • Road Striping	$0
1-R Preventive Rehabilitation	• Chip Seal • Micro-surface • Thin Overlay (<2”)	$60,000
2-R Minor Rehabilitation	• Surface Preparation (mil, level, full-depth reclamation, or combination thereof) • Thick Overlay (>2”) • Seal Coat	$250,000
3-R Preventive Rehabilitation with Shoulder Needs	• 1-R plus shoulder or widening requirements • Applicable on roads in good condition with shoulder needs	$350,000
4-R Major Rehabilitation	• 2-R plus shoulder or widening requirements • Applicable on narrow roads with shoulder or widening needs	$650,000
5-R Full Reconstruction	• Complete Reconstruction	$1,200,000

Huntington et al. (2013) proposed the decision tree shown in Figure 3.12 for identifying appropriate treatment types for Wyoming county paved roads. According to the decision tree, three variables are considered: PSI, road width, and rut depth. The PSI break points were established based on the *1993 AASHTO Guide* and ranking system of the WYDOT. According to the *1993 AASHTO Guide*, local roads with a PSI of less than 2.0 have reached terminal serviceability, and road segments with a PSI of less than 1.0 are characterized as severely deteriorated pavement. Therefore, these roads are in need of more intense treatments. As the PSI increases, rehabilitation strategies are also determined based on rut depths and road widths. If PSI is more than 3.0 and road width is less than 26 feet, rehabilitation is warranted only after pavement widening to improve safety characteristics of the road.

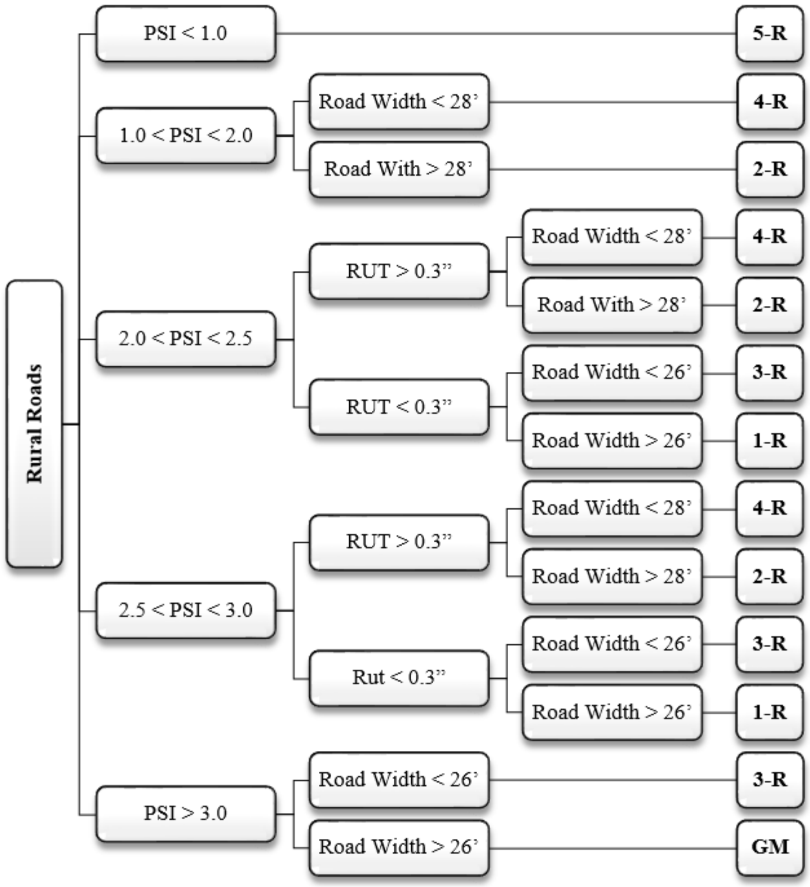


Figure 3.12 County Paved Road Treatment Decision Tree

Rut depth becomes a deciding factor when choosing between a thin overlay or a chip seal, and a more intense surface treatment or a thicker overlay. Rut depth of 0.3 inches is used as the break point in this analysis, as WYDOT deems rut depths in excess of 0.3 inches to be hazardous. Excessive rut depths, RUT > 0.3 inches, must be treated before any overlay can be placed on a road segment; therefore, high rut depth values will warrant more extensive treatment methods. Roads with lower rut depths, RUT < 0.3 inches, may be treated with a chip seal or a thin overlay.

Many of the paved county roads analyzed in this study are constructed with very narrow lanes and shoulders. Road width affects many aspects of road performance, including capacity, travel speed, and safety. The width of a road determines the feasibility of placing overlay pavements on existing surfaces. According to AASHTO's *A Policy on Geometric Design of Highways and Streets*, commonly referred to as the "Green Book," lane widths of 12 feet are generally provided in the design of two-lane highways with expected high percentages of commercial vehicles, such as oil and gas trucks (AASHTO, 2011). In addition, shoulders on paved roadways increase lateral clearance and improve capacity while accommodating stopped vehicles and emergency uses. They also provide lateral support for the sub-base, base, and surface courses. Therefore, the presence of a shoulder is essential on paved roadways. The Green Book recommends a minimum 2-foot shoulder width on minor rural roads. It states that "roads with a narrow traveled way, narrow shoulders, and an appreciable traffic volume tend to provide poor service, have a relatively higher crash rate, and need frequent and costly maintenance." On the basis of the design parameters regarding road width and shoulder presence, local paved roads should have enough width for 12-foot lanes with at least some shoulder to properly service the oil and gas industry. Therefore, thin overlays were recommended only for roads 26 feet wide or wider. Thick overlays were only recommended for roads 28 feet wide or wider (Huntington et al., 2013). Setting these roadway width parameters ensures that road widths following treatment are adequate to safely and efficiently serve oil and gas traffic.

3.4.2 Risk-Based Pavement Management System

The proposed PMS for county roads considers not only the risk but also local conditions, such as average daily truck traffic (ADTT), average daily traffic (ADT), and overall PSI. The objective of the developed model is to maximize overall expected PSI, maximize treated sections with high traffic, and minimize risk. See Equation 3.7.

$$Maximize \sum_{i=1}^{n} ADT_i * ADTT_i * Risk_i(Treatment\ type) * Expected\ PSI_i(Treatment\ type) * x_i \tag{3.7}$$

where,
ADT_i and $ADTT_i$ are the average daily traffic and average daily truck traffic for road i
$Risk_i$ and expected PSI are functions of treatment type
x_i is an integer equal to 1 if the project is selected and 0 if it is not selected

This is a combinatorial optimization problem in which one selects a collection of projects of maximum value while satisfying some weight constraint. More formally, the problem can be written as in Equations 3.8 through 3.10.

$$Maximize \sum_{i=1}^{n} ADT_i * ADTT_i * Risk_i(Treatment\ type) * Expected\ PSI_i(Treatment\ type) * x_i \tag{3.8}$$

$$Subject\ to \sum_{i=1}^{n} Treatment\ Cost_i * x_i \leq budget \tag{3.9}$$

$$x_i \in \{0,1\} \tag{3.10}$$

As mentioned in previous sections, the following treatments are normally applied to county paved roads: GM, 1-R, 2-R, 3-R, 4-R, and 5-R. As treatment cost increases, risk also increases. For example, the cost of 3-R treatment is 54% lower than that of 4-R treatment. So the risk of 3-R treatment is also 54% lower than that of 4-R treatment. The variation of treatment costs and risk can be seen in Figure 3.13. In this research, the risk ranges between 0 and 1, where 1 represents high-risk roads that require immediate treatment and 0 represents no-risk roads. For 4-R treatment type, risk was considered as the highest because treatment cost will be substantially higher if the 4-R treatment is not applied. When 5-R treatment is appropriate for a specific road, risk is the lowest (0.05). This is because the road already requires full replacement. Therefore, applying immediate treatment does not reduce the life-cycle cost in any way.

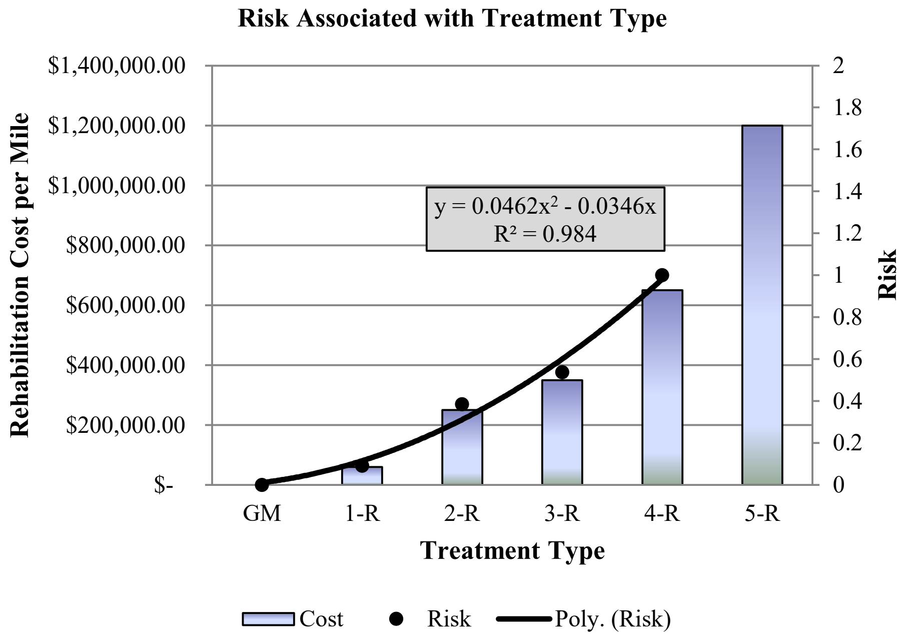


Figure 3.13 Variation of Risk Associated with Treatment Cost

The risk and expected PSI can be determined using Equations 3.11 and 3.12.

$$Risk_i = \begin{cases} 0.05 & if\ Treatment\ Type = GM \\ 0.092 & if\ Treatment\ Type = 1-R \\ 0.385 & if\ Treatment\ Type = 2-R \\ 0.538 & if\ Treatment\ Type = 3-R \\ 1.0 & if\ Treatment\ Type = 4-R \\ 0.05 & if\ Treatment\ Type = 5-R \end{cases} \quad (3.11)$$

$$Expected\ PSI_i = \begin{cases} 3.9, & if\ Treatment\ Type = 1-R \\ 4.0, & if\ Treatment\ Type = 2-R \\ 4.0, & if\ Treatment\ Type = 3-R \\ 4.1, & if\ Treatment\ Type = 4-R \\ 4.3, & if\ Treatment\ Type = 5-R \end{cases} \quad (3.12)$$

The GM is applied on all the roads not selected for implementing treatments (1-R to 5-R). The selected model can be used to satisfy any budget limit. This algorithm can also be used to prepare a five-year capital improvement plan (CIP) for pavements. In this regard, it is very important to predict next year's pavement condition based on the existing condition. Pavement condition is represented by PSI and rut depth (RD). WYDOT provided the necessary data to develop the pavement performance model for county roads. The models can be seen in Equations 3.13 and 3.14, where PSI represents present serviceability index and RD is rut depth in a specific year. Pavement age can be determined using existing PSI and RD values of a road. The optimization formulation used in this research has been solved using the generalized reduced gradient nonlinear algorithm.

$$Pavement\ Age = 0.00005 * PSI^3 - 0.0029 * PSI^2 - 0.0306 * PSI + 4.2744 \quad (3.13)$$

$$Pavement\ Age = 0.0000003 * RD^3 - 0.00008 * RD^2 + 0.0107 * RD + 0.00005 \quad (3.14)$$

3.4.3 Optimizing Maintenance Budgets

These optimization models consider the cost factor and local conditions, such as overall PSI and ADT, to optimize pavement maintenance planning. The cost factor is estimated ranging from 0 to 1, where 1 represents most expensive road and 0 is the lowest. For each roadway segment, there is a value of cost factor based on the treatment required. The objective of the developed model is to maximize overall expected PSI by selecting roads having higher traffic volumes with treatments at a lower cost factor. In this optimization model, the only constraint was budget. At a specific budget, the list of projects can be identified by using a linear programming technique taking into account the traffic volume and cost factor of each treatment. The optimum budget was determined by conducting a sensitivity analysis, in which the network PSI was estimated at different funding levels using the optimization model. The overall network PSI versus funding levels were plotted to investigate the rate of improvement per $1 million of spending. From this plot, the optimum budget was identified as the budget above which the rate of improvement (per $1 million of spending) is higher compared with the spending below the budget. The optimization model can be formulated as in Equations 3.15 through 3.17. This is a combinatorial optimization problem where one selects a collection of projects of maximum value while satisfying some weight constraint.

$$Maximize \sum_{i=1}^{n} \frac{Expected\ PSI_i(Treatment\ type) * ADT_i}{Cost\ Factor_i(Treatment\ type)} * x_i \quad (3.15)$$

$$Subject\ to \sum_{i=1}^{n} Treatment\ Cost_i * x_i \leq budget \quad (3.16)$$

$$x_i \in \{0,1\} \quad (3.17)$$

where,
ADT_i = average daily traffic for road *i*
Cost Factor and expected PSI are a function of treatment type
x_i = integer equal to 1 if the project is selected and 0 if it is not selected

The objective function of the optimization model represents that, when the cost factor is lower, the chance of selecting the road for maintenance is higher. At the same time, when ADT of a particular road is higher, the chance of selecting this road for maintenance is also higher. Combining the effect of cost factor and ADT, it can be said that when the cost factor is lower for a road with higher ADT, the chance of selecting that road improvement is even higher.

As mentioned in previous sections, the following treatments are normally applied to county paved roads: GM, 1-R, 2-R, 3-R, 4-R, and 5-R. Figure 3-14 shows the relationship between rehabilitation cost and treatment types. As expected, extensive treatments cost more. In addition, as treatment cost increases for a particular roadway segment, the cost factor also increases. This cost factor is based on the rate of deterioration of segments. Newer segments have a low rate of deterioration, and as a result, their treatments have a lower cost factor. On the other hand, segments requiring extensive treatments have a higher cost factor. It is always more cost effective to keep pavement segments in good shape instead of waiting for the segments to begin deteriorating rapidly, which would result in spending more on the expensive treatments. If roadway segments that require minor rehabilitation are not rehabilitated immediately, major rehabilitation will be required in the near future. That increases the overall life-cycle cost of the network significantly. In this study, roadway segments requiring minor rehabilitation are considered as roads with lower cost factors. For example, the cost of 3-R treatment is 54% lower than 4-R treatment. Therefore, the cost factor of 3-R treatment is also 54% lower than 4-R treatment. The variation of treatment cost and cost factor can be seen in Figure 3.14.

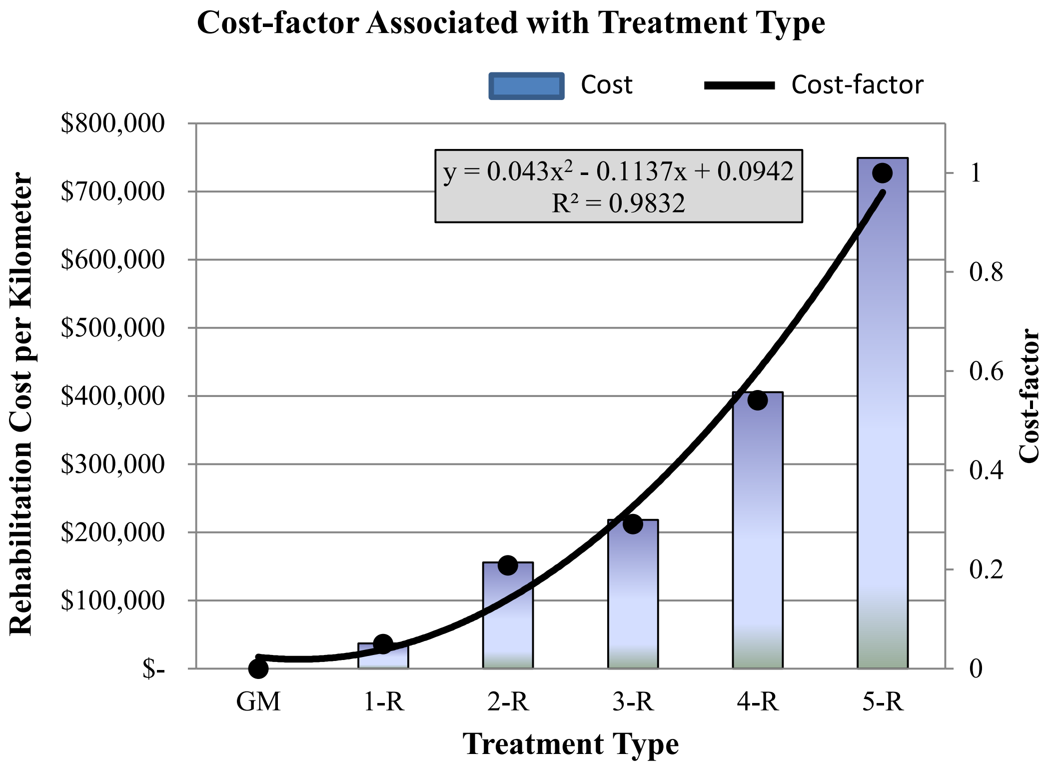


Figure 3.14 Variation of Cost Factor Associated with Treatment Cost

The cost factor can be determined using Equation 3.18. The value of cost factor for each treatment type is determined from the relationship developed in Figure 3.14, in which the secondary axis represents the value of cost factor at a specific treatment type. The threshold values in Equation 3.18 were determined from the relationship developed in Figure 3.14. The cost factor ranges between 0 and 1. When a roadway segment requires expensive treatments, the cost factor increases. For each specific treatment, the cost factor is estimated from the relationship. For the expected PSI, the same values of risk-based analysis can be considered. See Equation 3.12.

$$Cost\ Factor_i = \begin{cases} 0.000 & if\ Treatment\ Type = GM \\ 0.050 & if\ Treatment\ Type = 1-R \\ 0.208 & if\ Treatment\ Type = 2-R \\ 0.292 & if\ Treatment\ Type = 3-R \\ 0.542 & if\ Treatment\ Type = 4-R \\ 1.0 & if\ Treatment\ Type = 5-R \end{cases} \quad (3.18)$$

3.5 Optimization Methodology for Traffic Safety

Similar to a PMS, a Traffic Safety Management System (TSMS) is also very important in transportation planning. This section discusses the methodology to develop a TSMS following two steps: (1) crash hot spots, and (2) funding-allocation strategy.

Figure 3.15 shows the overall methodology for a TSMS optimization model. The methodology is primarily divided into two main steps: identification of crash hot spots, and allocation of funding for safety improvement. These steps are discussed in the following subsections.

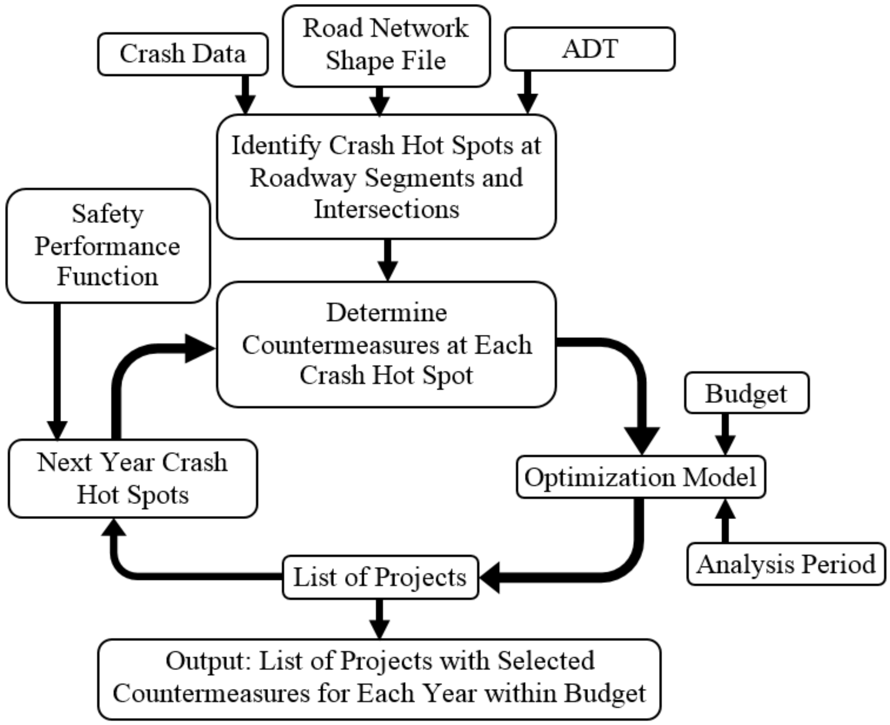


Figure 3.15 Research Methodology for TSMS Optimization Model

3.5.1 Crash Hot Spots

The Highway Safety Manual (HSM) discusses the techniques to identify crash hot spots in detail (AASHTO 2010). These techniques rank the roadway segments based on several factors, including average crash frequency, crash rate, relative severity index, critical crash rate, level of service of safety, and predicted crash frequency. Among these techniques, the empirical Bayes (EB) method was selected as the best technique to identify crash hot spots. The EB method is considered the most accurate technique for two main reasons: (1) it accounts for regression-to-the-mean bias, and (2) it estimates a threshold level of performance in terms of crash frequency or crash severity (AASHTO, 2010). In addition to these techniques, a significant amount of research was performed to identify crash hot spots using kernel density estimation (KDE), Moran's I index method, and Getis-Ord GI* (Cheng and Washington, 2008; Elvik, 2008; Persuad et al., 1999). These techniques were implemented using ArcGIS version 10.1 software.

In this study, the EB method was implemented to identify the crash hot spots. Five years of crash data from 2010 to 2014 were investigated. In the maintenance database used in PMS, the roadway segments were different in length. In order to compare the segments with each other in terms of crashes, the crashes for each segment were normalized by 1.0 mile.

3.5.2 Funding-Allocation Strategy

Saha and Ksaibati (2016b) discussed the funding allocation strategy for TSMS. They mentioned that after identifying the crash hot spots, all these potential crash hot spots cannot be selected for safety improvements because of limited funding. The selection of the safety projects primarily depends on the crash reduction and the costs associated with safety countermeasures. Optimization techniques can be applied to select the projects maximizing the crash reduction.

A sensitivity analysis was conducted using optimization techniques to determine the most appropriate budget for improving safety statewide. The objective function in the optimization model minimizes the overall expected crashes after implementing the safety improvements. After selecting the crash hot spots, all these hot spots may not be selected for safety improvements due to a limited budget. For each crash hot spot, the safety countermeasures were selected and the costs were estimated.

where,
N_i and $N_{f\&Ii}$ = predicted crashes and fatal and injury crashes on road i, respectively
x_i = 1 if the project is selected and 0 if it is not selected

Table 3.7 lists the safety countermeasures associated with costs and the crash reduction factor (CRF). The CRF can be defined as the expected percentage of crash reduction after implementing a safety countermeasure at a specific location. Also, while applying different treatments for pavement preservation, there might be significant safety impacts during construction. The impacts vary for different treatment types. For simplicity, the safety aspects during construction were not considered in this study. The overall optimization model is shown in Equations 3.20 through 3.22. This is a combinatorial optimization problem, which selects a collection of projects of minimum value while satisfying some constraint. The predicted crashes were estimated using the safety performance function (SPF) proposed in the Highway Safety Manual (AASHTO 2010). The SPF estimates the predicted crashes as a function of ADT. If a roadway segment is selected for safety improvements, the predicted crashes will be recalculated and multiplied by the CRF.

$$Minimize \sum_{i=1}^{n} N_i$$
$$Minimize \sum_{i=1}^{n} N_{f\&I_i} \tag{3.20}$$

$$Subject\ to \left(\sum_{i=1}^{n} Safety\ Improvement\ Cost_i * x_i\right) \leq budget \tag{3.21}$$

$$x_i \in \{0,1\} \tag{3.22}$$

where,
N_i and $N_{f\&Ii}$ = predicted crashes and fatal and injury crashes on road i, respectively
x_i = 1 if the project is selected and 0 if it is not selected

Table 3.7 CRF and Cost of each Safety Countermeasures for Paved County Roads

Countermeasure	**Unit cost**	**CRF(%)**
Install guide signs (general)	$400	15
Install advance warning signs (positive guidance)	$400	40
Install chevron signs on horizontal curves	$400	35
Install curve advance warning signs	$400	30
Install delineators (general)	$500	11
Install delineators (on bridges)	$300	40
Install centerline markings	$0.66/LM	33
Improve sight distance to intersection	$4.92/LM	56
Install guardrail (at bridge)	$197/LM	22
Install guardrail (outside curves)	$49/LM	63
Install transverse rumble strips on approaches	$500	35
Lengthen culvert	$492/LM	40

Note: LM = linear meter

3.6 Chapter Summary

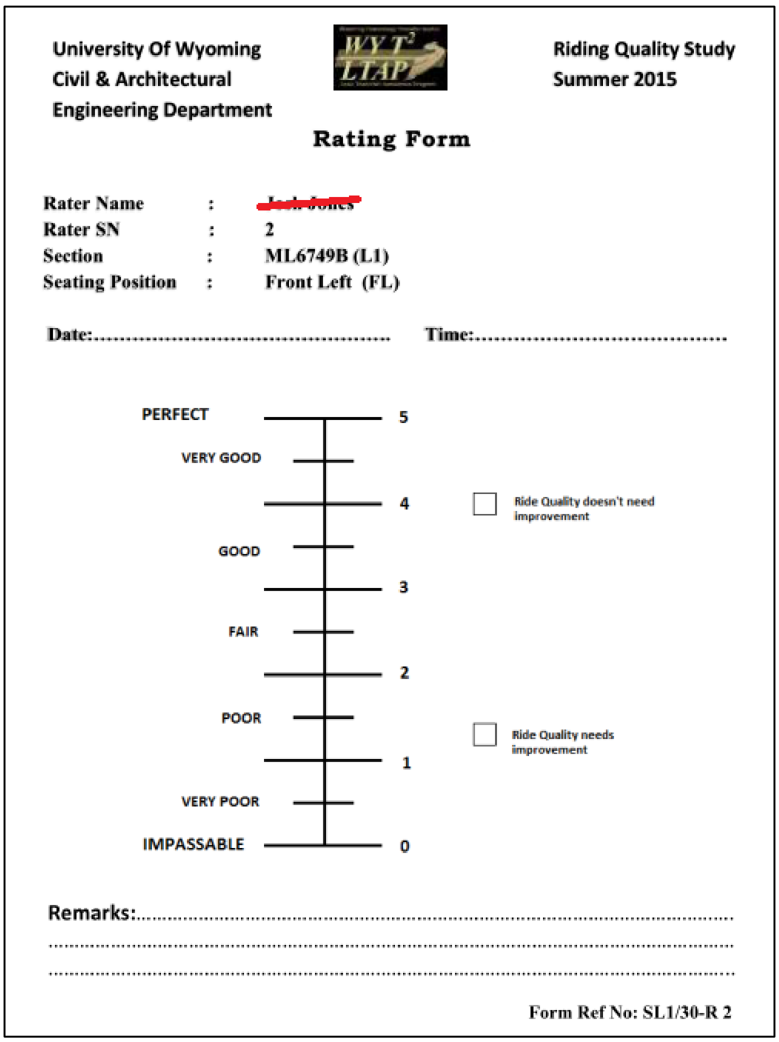
This chapter explains the overall research methodology and detailed formulations of pavement performance modeling and optimization analysis conducted on Wyoming's county paved roads. Roadway condition data were collected. The collected data included the different roadway condition indices (rut, IRI, and PCI). Design of experiment is one of the most important parts of any research study. Two separate experiments were designed. The first includes a riding quality survey design in order to develop serviceability prediction models. Two vehicles, a sedan and an SUV, were used to reflect the normal driving scenarios in Wyoming. Ten Wyoming panelists from various locales were selected to do the rating process. These panelists represented different backgrounds. The riding quality survey was performed on 30 roadway segments that included various levels of roadway condition indices. The second experiment was designed to evaluate the ability of modern smartphones to return reliable roughness measurements. A sedan vehicle using two smartphones was used to collect the accelerometer data. The accelerometer data were collected over 20 roadway segments. The selected segments reflected the actual roadway segments under any PMS. In addition, the research developed multiple optimization models for county roads to maximize different management performance parameters for pavement preservation and traffic safety associated with risk-based analysis and budget constraints. The primary factors in these models included pavement serviceability index, traffic volume, cost factor, roadway inventory, crash data, crash modification factor, and safety improvement countermeasures. The findings will help lawmakers make funding decisions to preserve county roadway networks.

4. DEVELOPMENT OF SERVICEABILITY PREDICTION MODELS

The PSI models for county paved roads were developed in this chapter. Section 4.1 presents the procedures followed to deliver the present serviceability rating, while section 4.2 discusses the process of analyzing data in order to develop the county serviceability model.

4.1 Present Serviceability Ratings (PSR)

During the survey, rating forms were distributed to the raters. These forms included the rater's name, seating position, and the roadway segment being rated. Figure 4.1 shows the rating form used during the riding quality survey. Raters were asked to mark a point on the shown scale reflecting the degree of their comfort level. For each roadway section, the mean panel ratings (MPR) were considered the PSR for that section.



University Of Wyoming
Civil & Architectural
Engineering Department

Riding Quality Study
Summer 2015

Rating Form

Rater Name : [redacted]
Rater SN : 2
Section : ML6749B (L1)
Seating Position : Front Left (FL)

Date:.. Time:..

PERFECT — 5
VERY GOOD
— 4
GOOD
— 3
FAIR
— 2
POOR
— 1
VERY POOR
IMPASSABLE — 0

☐ Ride Quality doesn't need improvement

☐ Ride Quality needs improvement

Remarks:...
....
....

Form Ref No: SL1/30-R 2

Figure 4.1 Rating Form

For the rating process, 10 raters rated the 30 sections in three trips using the SUV vehicle, and six raters out of the previous group rated the same sections using the sedan vehicle in two trips. Table 4.1 shows a summary of the Wyoming riding quality experiment. Notice that 95% of the IRI measurements fall in the range of 60 in/miles to 373 in/miles and 95% of PCI values fall between 43 and 100. Regarding rutting depth, 95% of the values fall in the range of 0.004 in. to 0.364 in. This gives an indication of the wide distribution of the selected roadway segments that cover the different categories of roadway condition indices.

Table 4.1 Summary of Wyoming Riding Quality Experiment

Location	**Number of Participants**	**Number of Test Segments**	**Test Vehicles**	**Index**	**Mean**	**Standard Deviation**	**Measurement system**
Wyoming	10	30 (Flexible only)	Sedan (2011 Ford Fusion), SUV (4WD 2014 Ford Explorer)	IRI	178.8	97.3	South Dakota Profiler
				PCI	78.2	17.2	Video Logs
				Rut	0.184	0.09	Path Runner

4.2 Serviceability Data Analysis

The PSI models for county paved roads were developed as in the following sections.

4.2.1 Prediction Models

The obtained ratings for the 30 sections were entered into a spreadsheet along with the different distresses for every pavement section. One section was excluded from the analysis, as it was under reconstruction during the rating process. The individual rater's performance was examined by plotting the individual panel ratings versus the mean panel rating. After examining each rater's performance when compared with the group, it was found that rater R8 rated all sections higher than others. Therefore, he was considered an outlier and excluded from the data analysis (Figure 4.2). For other raters, there was no major difference or discrepancy since all the points were on or near the unity line. The individual panel ratings versus group plots are shown in Appendices A-5 and A-6 for the SUV and the sedan vehicles, respectively.

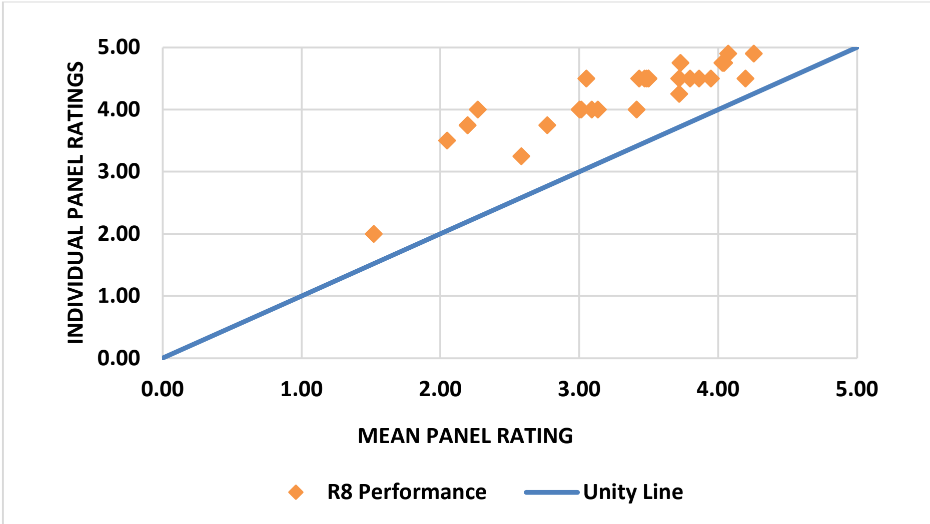


Figure 4.2 Performance of Rater (R8) Compared to the Group

The Shapiro-Wilk's test was used to test the normality of the mean panel ratings (MPR). The obtained P-values from the test were 0.0688 and 0.0673 for the SUV and sedan vehicles, respectively. Since these values are greater than 0.05, the MPR data were considered to be normally distributed for the riding quality ratings using both vehicles.

The Bartlett's test was used to test the homogeneity of variances among the different raters. Table 4.2 shows the Bartlett's test analysis results for both vehicles. Since the values of T-statistics are less than the values of $X^2_{1-\alpha,k-1}$, the hyporeport was acceptable and the variances were homogeneous at a significance level of α=0.01 for both vehicles.

Table 4.2 Bartlett's Test Results

Parameters	**SUV Vehicle**	**Sedan Vehicle**
T-Statistics	13.797	9.215
k	9	5
$X^2_{1-\alpha,k-1}$	20.09	13.3
α	0.01	0.01

The variance analysis results using an F-test showed the variance of the raters' age, gender, and different seating positions were not significantly different from each other. Hence, it did not affect the rating process (F<F critical) at a significance level of α=0.01.The F-test results are shown in Table 4.3.

Table 4.3 F-Test Results

Parameters	Seating (SUV)		Seating (Sedan)		Gender		Age	
	Front	**Back**	**Front**	**Back**	**Female**	**Male**	**Old**	**Young**
Mean	2.931	3.386	2.193	2.718	3.052	3.352	3.118	3.418
Variance	0.696	0.392	0.960	0.391	0.819	0.404	0.481	0.433
Observations	29	29	28	28	29	29	29	29
df	28	28	27	27	28	28	28	28
F	1.775		2.454		2.026		1.112	
P(F<=f) one-tail	0.067		0.011		0.033		0.391	
F Critical one-tail	2.464		2.507		2.464		1.882	

The T-test analysis showed there was a significant difference between the MPRs using different vehicles (t >t critical), as shown in Table 4.4.

Table 4.4 T-test Analysis Results

Parameters	**SUV**	**Sedan**
Mean	3.348	2.716
Variance	0.403	0.323
Observations	26	26
Pooled Variance	0.363	
Hypothesized Mean Difference	0	
df	50	
t Stat	3.780	
P(T<=t) one-tail	0.000	
t Critical one-tail	2.403	
P(T<=t) two-tail	0.000	
t Critical two-tail	2.678	

The multiple regression analysis was performed using Microsoft Excel and R-Studio. Table 4.5 shows the correlation matrix between the potential variables to predict PSR.

Table 4.5 Correlation Matrix Using Sedan Data

	Rut	**IRI**	**PCI**	**PSR**
Rut	1.00	0.60	-0.62	-0.72
IRI	0.60	1.00	-0.55	-0.86
PCI	-0.62	-0.55	1.00	0.72
PSR	-0.72	-0.86	0.72	1.00

Multicollinearity can be noticed among the different independent variables. For example, the correlation between IRI and rut is 0.60, which is greater than 0.5. The same can be noticed from the dot matrix plot shown in Figure 4.3. The effects of the existent multicollinearity will be discussed at the end of the diagnostic analysis section.

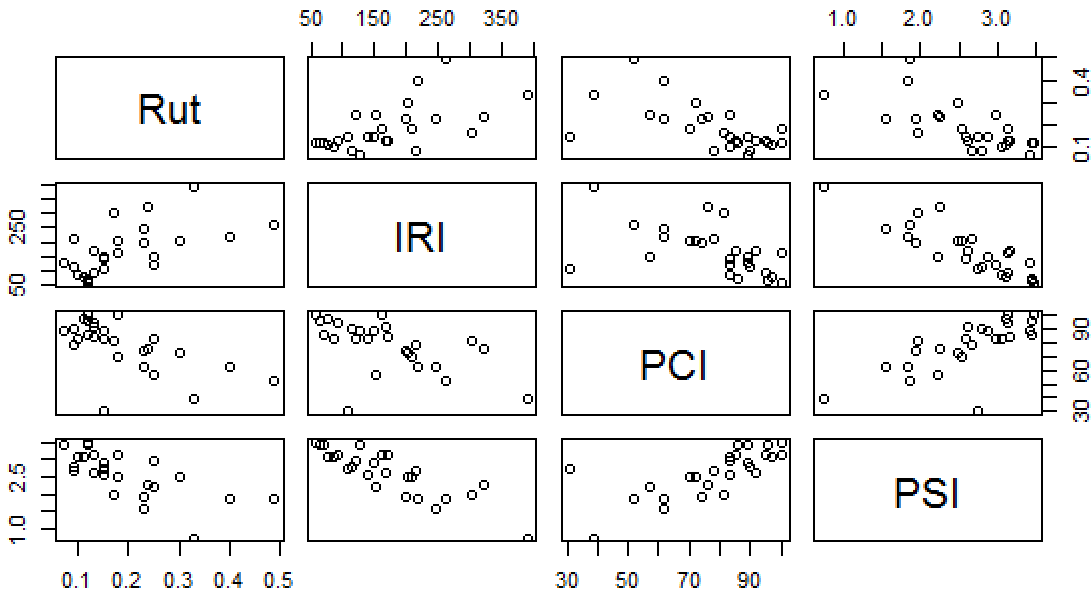


Figure 4.3 Dot Matrix Plot (Sedan)

The modeling process was initialized by fitting a simple linear model that included all the variables, as shown in Table 4.6. Notice that rut is not significant to the model (P-value > 0.05). However, rut must be kept in the model as previous studies included rut in their models (i.e., WYDOT model).

Table 4.6 Simple Model Fitting (Sedan)

Coefficients	Estimate	Std. Error	T-Value	Pr(>| t |)
Intercept	2.822	0.442	6.379	1.65e-06
IRI	-0.005	0.001	-5.471	1.46e-05
Rut	-1.225	0.756	-1.621	0.19
PCI	0.011	0.004	2.32	0.015

Moreover, the residuals versus interaction term plots did not suggest any addition for interaction terms to the model. For example, Figure 4.4 shows a plot between the interaction term (Rut*PCI) and the residuals. The plot does not show any trend that implies the addition of this interaction term to the model. The same behavior can be noticed for the other interaction terms, such as PCI-PCI, IRI-Rut, IRI-PCI, etc.

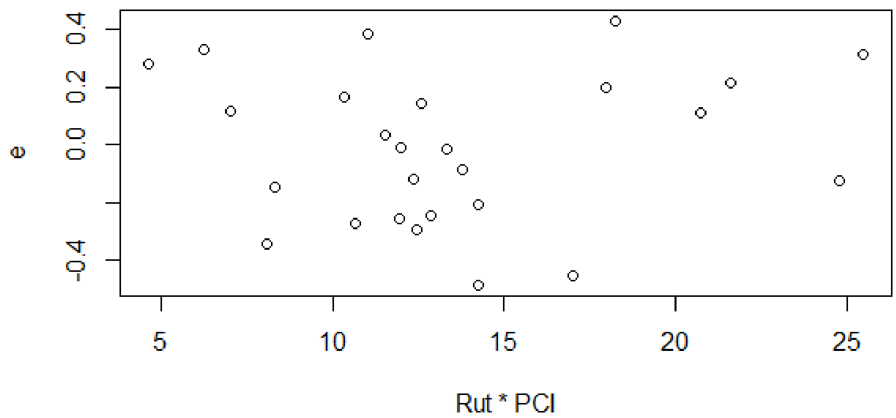


Figure 4.4 Residuals vs. Interaction Term – Rut*PCI (Sedan)

Using a simple linear regression model may lead to negative predictions in the PSR values, especially with high IRI values as in the county roads case. Thus, IRI was transformed into an exponential form. Also, the transformation helped improve the linearity of the residuals. It was found that the transformation of IRI to $e^{-0.003*IRI}$ fits the data best. Also, in a trial to produce a model that looks similar to the WYDOT model, the following transformed variables were added to the pool of variables: Rut^2 and (1-PCI/100). The simplicity implied by the transformed variables will give the new model the required general acceptability and applicability.

Finally, using multiple regression on a pool of variables that includes ($e^{-0.003\ IRI}$, Rut^2, (1-PCI/100)), the following model (Equation 4.1) can be produced for the sedan vehicle:

$$PSI = 1.185 + 2.892e^{-0.003IRI} - 1.469Rut^2 - 1.247\left(1 - \frac{PCI}{100}\right) \quad (4.1)$$

R^2 =0.80, MSE=0.08

where,

IRI=international roughness index (in/miles)

Rut=the rut depth (in)

PCI=pavement condition index

Notice that Equation (4.1) fits the data with high significance. The new model can explain 80% of the variations among the PSR values. Table 4.7 shows a summary of statistics for the fitted model (Equation 4.1). Again, it can be seen that rutting is not significant to the model.

Table 4.7 Final Model Fitting (Sedan)

Coefficients	**Estimate**	**Std. Error**	**T-Value**	**Pr(>| t |)**
Intercept	1.185	0.393	3.017	0.00614
$e^{-0.003\ IRI}$	2.892	0.529	5.459	1.5e-05
Rut^2	-1.469	1.444	-1.017	0.319
1-PCI/100	1.247	0.429	-2.905	0.008

The same procedure discussed earlier can be followed in order to fit a model for the SUV data. Equation 4.2 shows the final model developed for the SUV vehicle.

$$PSI = 1.219 + 3.3e^{-0.002IRI} - 4.122Rut^2 - 0.475\left(1 - \frac{PCI}{100}\right) \qquad (4.2)$$

R^2=0.76, MSE=0.09

where,
IRI=international roughness index (in/miles)
Rut=the rut depth (in)
PCI=pavement condition index

4.2.2 Diagnostic Analysis

In order to check the statistical validity of the developed models, diagnostic analyses were performed to check the main assumptions of the linear regression. These assumptions are as follows (Kutner et al., 1996):

1. Linearity
2. Outlier effects
3. Homoscedasticity (constant variance)
4. No autocorrelation (independency of the error terms)
5. Normality of the error distribution
6. Multicollinearity

Figure 4.5 shows the residuals versus the fitted values plots. It can be noticed that the observations are distributed evenly (approximately) around the line (h=0). Hence, both models meet the linearity assumption. Also, the plots show a constant trend of the variance. The residuals approximately stay the same as the fitted values increase. In addition, the plots do not show any clustering between the residuals. Therefore, both models achieve independency among the error terms.

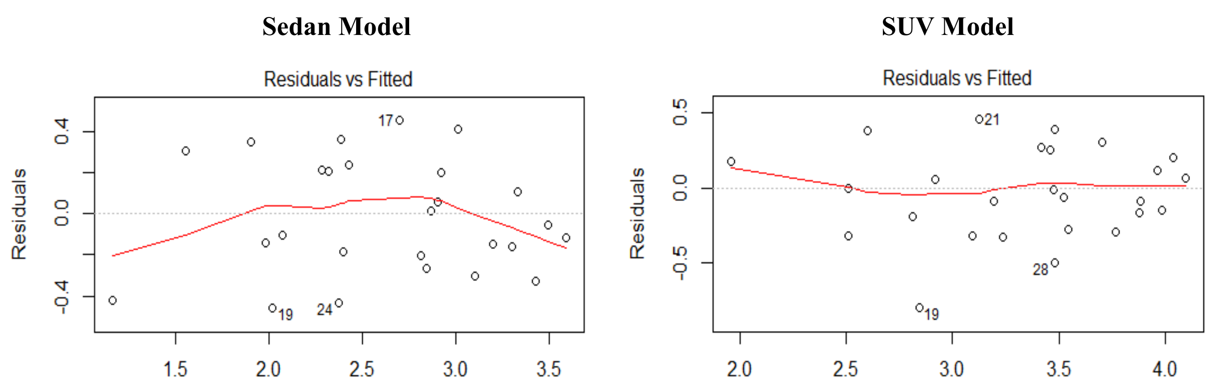


Figure 4.5 Residuals vs Fitted Values Plots

Regarding normality, Figure 4.6 shows Q-Q plots for both models. Residuals are approximately falling on the diagonal line with slight deviations. Hence, residuals show normal behavior. In addition, the Shapiro-Wilk's test results confirm the same, as P-values are 0.16 and 0.4 for sedan and SUV models, respectively, which are greater than 0.05.

Sedan Model **SUV Model**

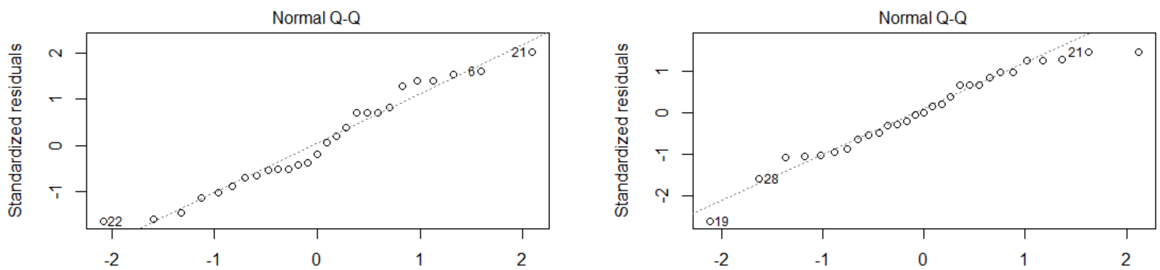


Figure 4.6 Q-Q Plots

Figure 4.7 shows the standardized residuals versus fitted values plots. It can be seen that none of the points fall outside the 3σ interval. Hence, outlier points do not exist. Going back to the multicollinearity, Table 4.8 shows the variance inflation factors (VIF) for the used variables. It can be noticed that all of the VIFs are less than 10. Hence, multicollinearity is not an issue that may affect the predicted results.

Sedan Model **SUV Model**

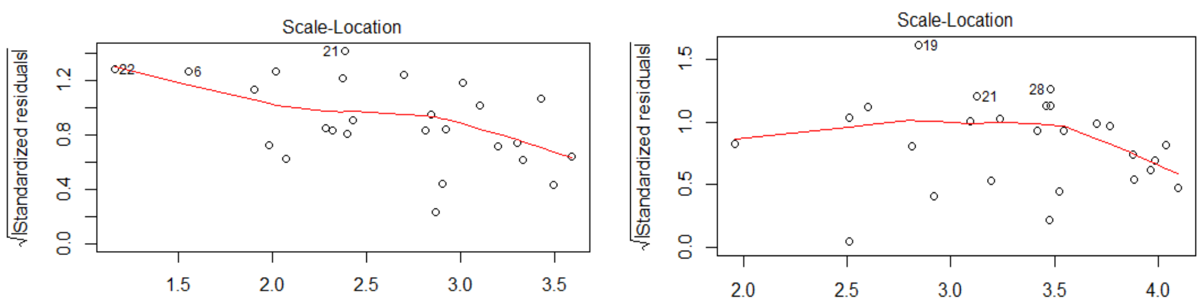


Figure 4.7 Standardized Residuals vs Fitted Values

Table 4.8 Variance Inflation Factors (Sedan)

Model	$e^{-0.003\ IRI}$	Rut^2	1-PCI/100
Sedan	1.594	1.694	1.686
SUV	1.201	1.683	1.578

4.2.3 Comparison between the Developed Models

To compare the developed models and the WYDOT model, they were applied on the Wyoming county roads' dataset, as shown in Figure 4.8. It can be observed that the newly developed models tend to give higher expectations than the WYDOT model, which is reasonable since the WYDOT model was developed for the state's highway system. Hence, it is more sensitive to the different distress levels. Also, the SUV model tends to give higher predictions of PSR values than the sedan model. This can be explained since the SUV vehicle is more suitable for rough terrains and makes the ride more comfortable to the raters. This is observed when compared with the normal sedan vehicle, resulting in a more optimistic model.

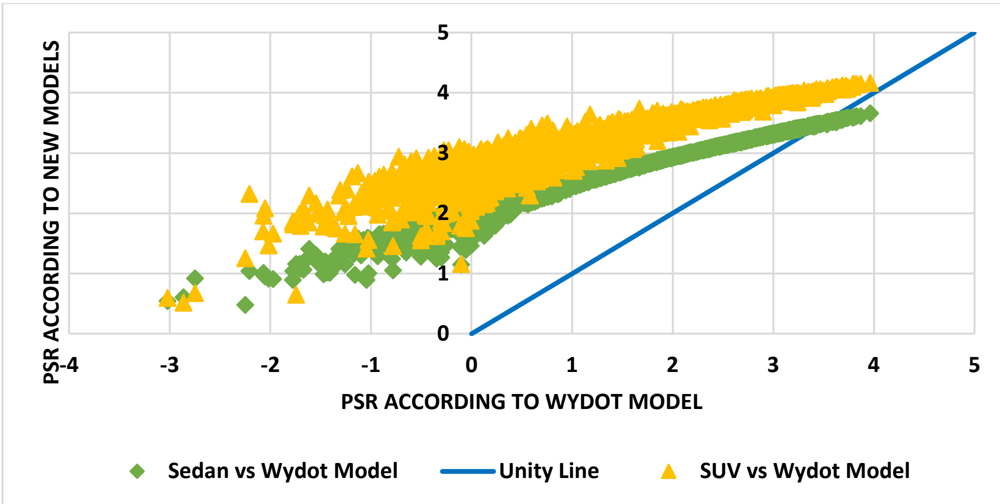


Figure 4.8 New Models versus WYDOT Model

Furthermore, according to the 1993 AASHTO Guide and WYDOT's ranking system for local roads (Huntington et al., 2013), a PSR value of 2 is considered the threshold for reconstruction works. Based on the WYDOT model, 68% of the local county roads need to be reconstructed. The newly developed models show that, of the county roads, 15% tested with the sedan model and 2% tested with the SUV model need to be reconstructed. This gives an indication that the WYDOT model underestimates the current status of the majority of the county road network. The highly optimistic perceptions for the newly developed models can be attributed to the fact that Wyoming drivers are conditioned to driving on these rough roads.

In order to check the reliability of the newly developed models and their validity for the rehabilitation analysis, a basic model was developed. This model is in Equation 4.3, which was developed using the ASTM approximation of the MPR discussed earlier in the methodology. See Table 3-5. The entire dataset is used in the validation process.

$$PSI = -0.259 + 4.35e^{-0.002IRI} + 0.237Rut^2 - 0.236\left(1 - \frac{PCI}{100}\right) \quad (4.3)$$

R^2 =0.94, MSE=0.02

Where:

IRI=international roughness index (in/miles)
Rut=the rut depth (in)
PCI=pavement condition index

Figure 4.9 shows a comparison between the WYDOT model and the ASTM model. It can be observed that the WYDOT model tends to give extremely lower predictions among all the PSR values, especially for PSR values less than 3.5. This gives another indication of the inadequacy of using this model to predict the status of county roads.

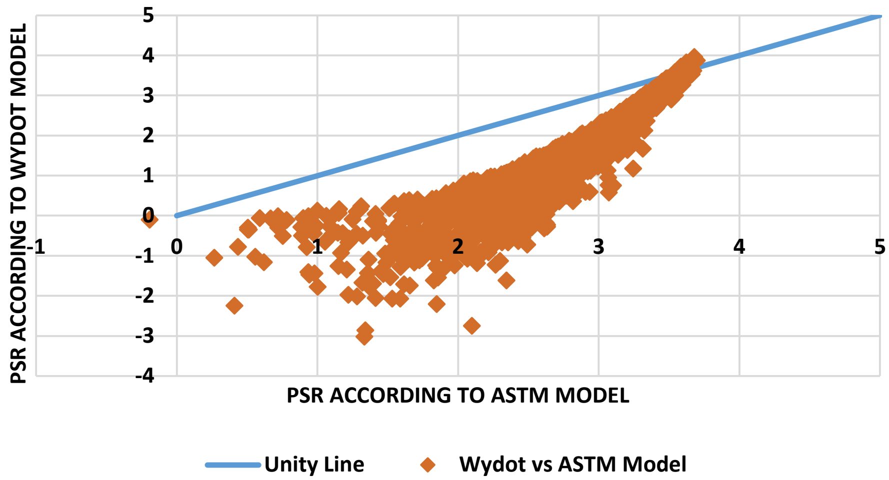


Figure 4.9 WYDOT Model vs ASTM Model

Figure 4.10 shows a plot for the newly developed models versus the ASTM model .When compared with the ASTM model, the sedan model almost gives the same expectations when PSR is greater than 3 and higher expectations when PSR is less than 1.8. Meanwhile, the SUV model tends to give higher expectations among all the PSR levels. According to the sedan model, the predicted PSR values are very close when the PSR is between 2.0 and 3.0. This indicates that the sedan model can be used for rehabilitation analysis purposes since this range of PSR values is the prime concern of the rehabilitation analysis (Gulen et al., 1994).

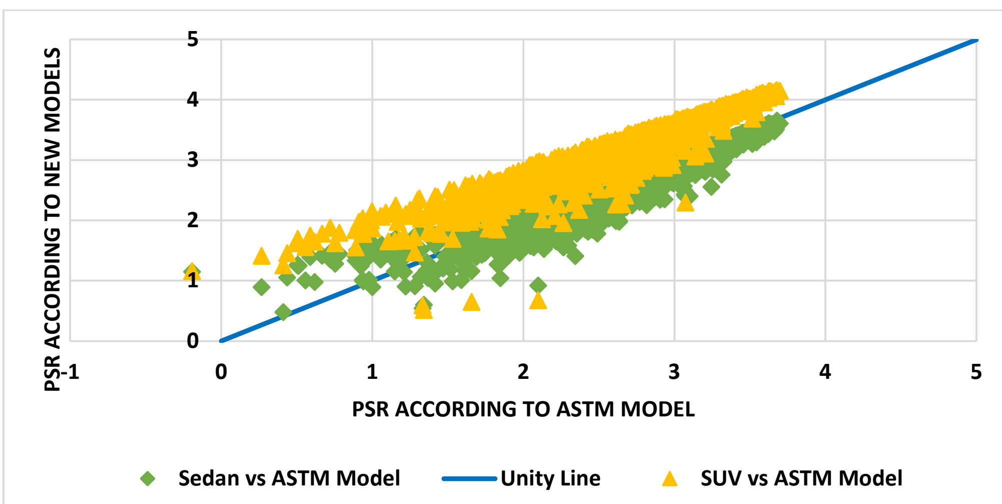


Figure 4.10 New Models Vs ASTM Model

Figure 4.11 shows the current condition of the county roads using the newly developed model (Equation 11). Note that it gives better distribution of the county road conditions among all the PSI levels. It decreases the total number of sections that require reconstruction (PSI<2) and increases the number of sections with acceptable conditions (2<PSI<3.5). This wide distribution of PSI values gives reasonable reflection of the general satisfaction among Wyoming residents with the majority of their county roads. This has great importance in the implementation of PMS and the funding allocation process for the county road network. When 68% of the roads are in very poor condition, it can be challenging to choose projects for rehabilitation when, according to the perceptions of actual county road users (Wyoming locals), only 15% of the roadway network is in very poor condition.

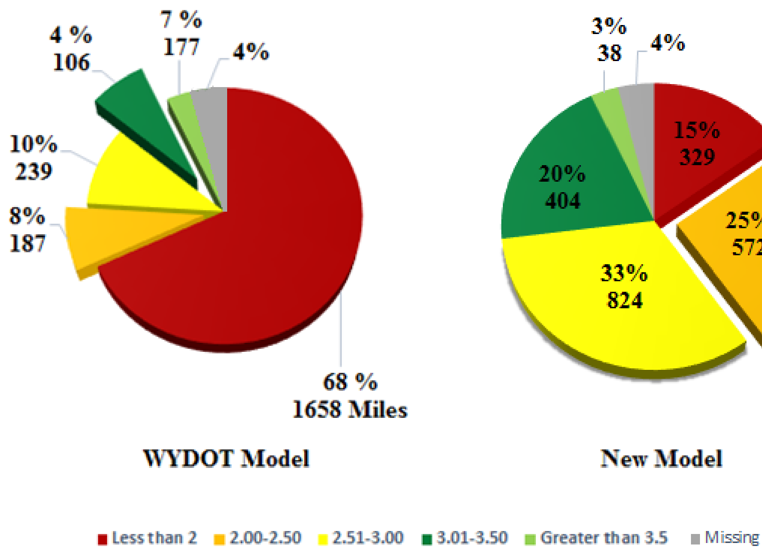


Figure 4.11 PSI of County Roads Using the Sedan and WYDOT Models

4.3 Chapter Summary

Using two vehicles, sedan and SUV, panel ratings were collected and combined with the related sections. Raters' performance, constant variance between the raters and normality of the ratings, were examined first. It was found that the rater's seating position, age, and gender were not significant to the rating process. However, the vehicle's type was significant. Using a multiple regression analysis, two models were fitted for each vehicle. The obtained models are highly significant. The adjusted R^2 values are 0.80 and 0.76 for the sedan and the SUV, respectively. Different diagnostic analyses were conducted later to verify the statistical validity of the new models.

A comparison between the WYDOT model and the new models (sedan and SUV) showed the WYDOT model underestimates the actual conditions of the local county roads according to the perceptions of local Wyoming drivers. Moreover, a new model was developed based on the ASTM approximation given for panel ratings. This model was used as base for comparison between the WYDOT and the new models. The comparison showed that the sedan model was more suitable for maintenance and rehabilitation purposes. Also, it was found that the sedan model gives a better distribution for the current conditions of county roads among the different serviceability levels. This reflects the general satisfaction of Wyoming locals toward the conditions of their county roads.

5. DEVELOPMENT OF IRI MODELS USING SMARTPHONES

The IRI evaluation using smartphones is presented in two main steps: pattern recognition analysis combined with model development and models validation. These different steps are presented in this chapter.

5.1 IRI Models Development

Accelerometer data were extracted from smartphones, uploaded to a computer, and imported into MATLAB for further analysis. After applying median and moving average filters on Samsung Galaxy SIII data, cross-correlation was applied to the different signals among the various IRI categories. For example, Figure 5.1 shows the cross correlation between a signal, measured over a roadway segment with IRI = 113 in/mile at 40 mph, and other signals measured within the different IRI categories (Table 2-3) at the same speed. The cross-correlation yielded a high amplitude among a wide range of lags over the five IRI categories. This indicates a high similarity in shape among the different measured signals. Thus, there are no unique features using cross-correlation that could identify these signals. The same basic result can be seen after applying the cross-correlation among all the 20 measured signals for both speeds. Applying the cross-correlation analysis on the Sony Xperia data yielded the same results. Roughness does not significantly affect the shape of the produced signals. Thus, the cross-correlation method does not provide a feature that allows the desired discrimination and classification of the different IRI categories.

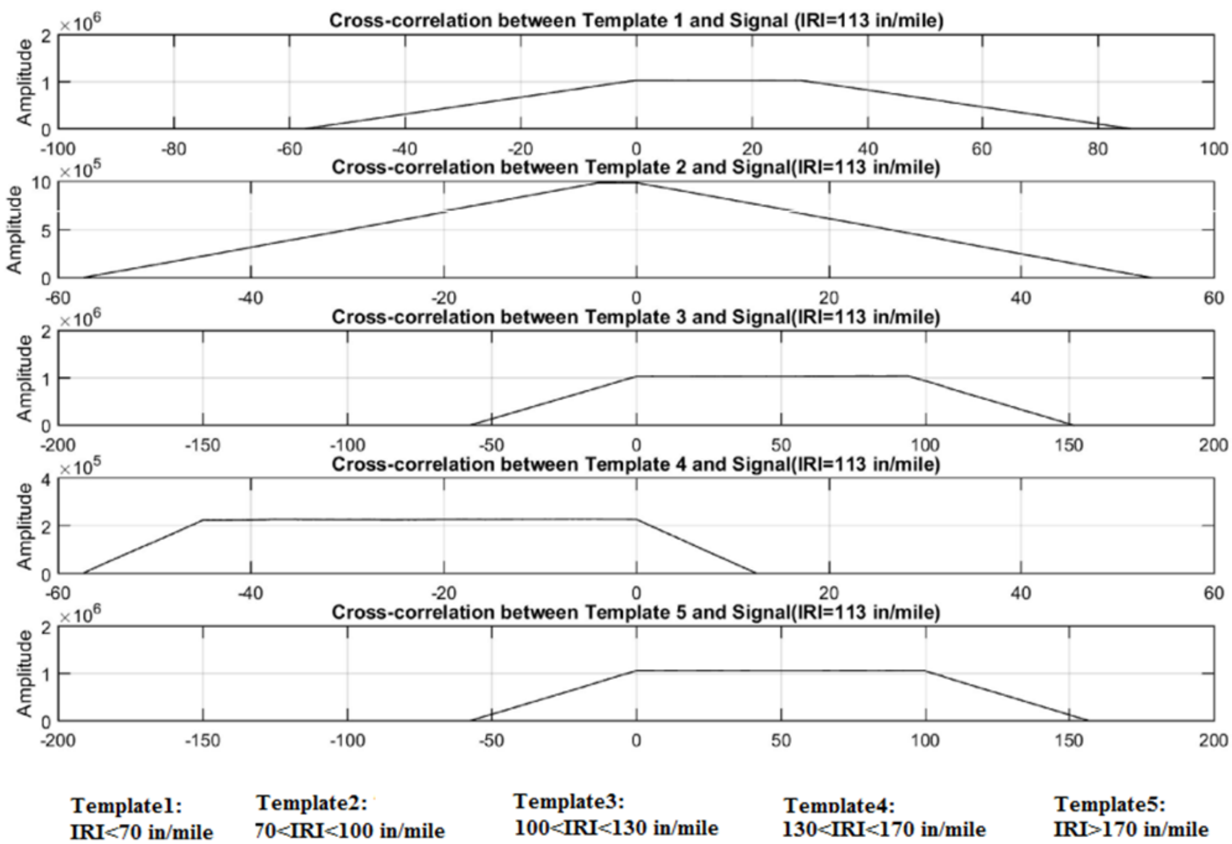


Figure 5.1 Cross Correlation between Signal (IRI=113 in/mile) vs IRI Categories (Using Samsung Galaxy SIII)

Figure 5.2 shows the Welch periodogram estimates of the PSD for different signals measured using a Samsung Galaxy SIII at 50 mph. This estimate was calculated using the Pwelch command of the MATLAB Signal Processing Toolbox, using the default parameters for segments, smoothing window, and overlap. The figure also shows that these signals have almost the same PSD at different frequencies. None of these plots show a unique PSD trend that could allow the signals to be used to discriminate between the different IRI categories.

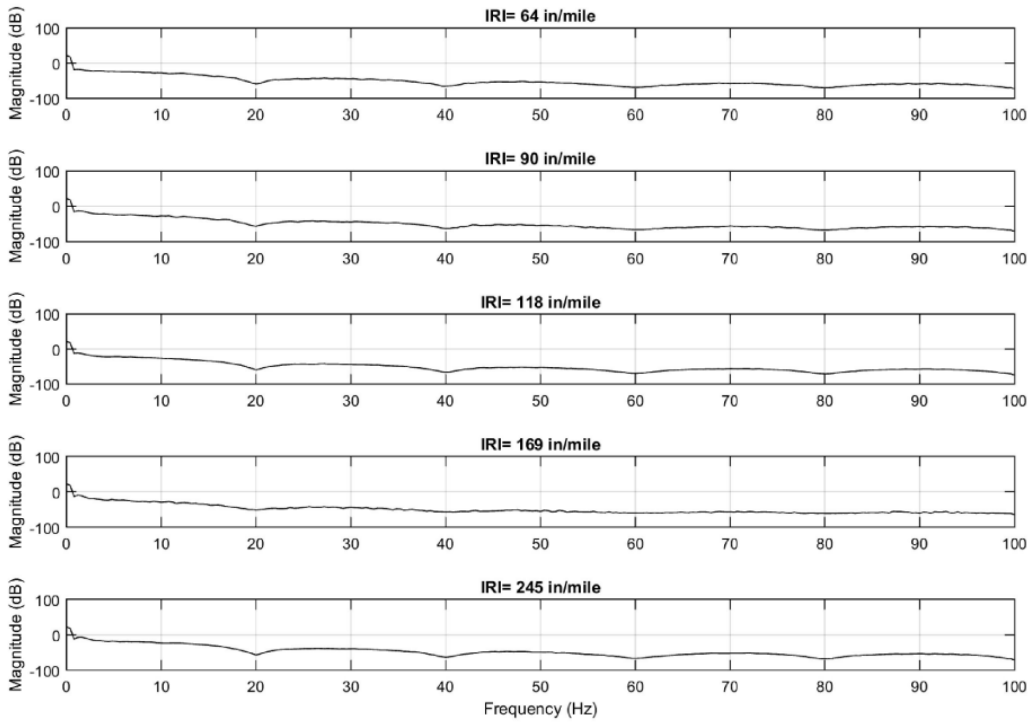


Figure 5.2 Welch Transformation (Using Samsung Galaxy SIII)

The Welch periodogram estimates of the PSD for the same signals measured using a Sony Xperia are shown in Figure 5.3. Again, these signals appear to have a very similar PSD trend without any unique features. Different roughness levels do not seem to have a specific effect on PSD of these signals. However, the measured signals using both smartphones showed a depression in the signal energy at 20 Hz. This can be attributed to the effect of the vehicles' suspension system. Further investigations are required to clarify this trend. The MATLAB code used in the cross-correlation and Welch peridogram estimates is shown in Appendices A-7 and A-8, respectively.

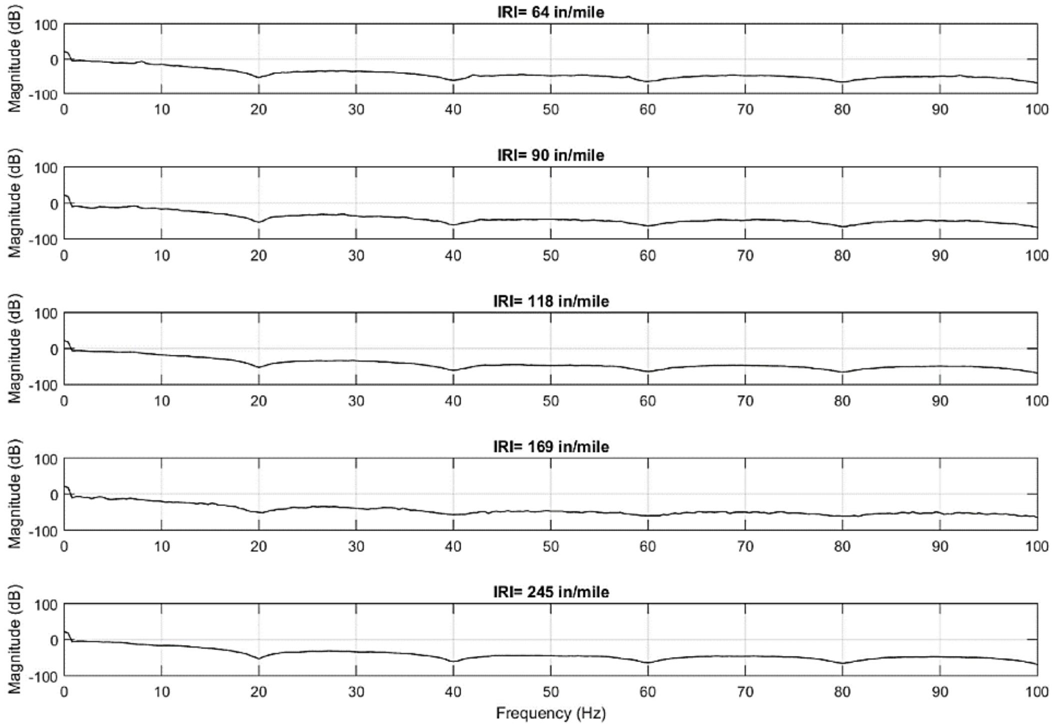
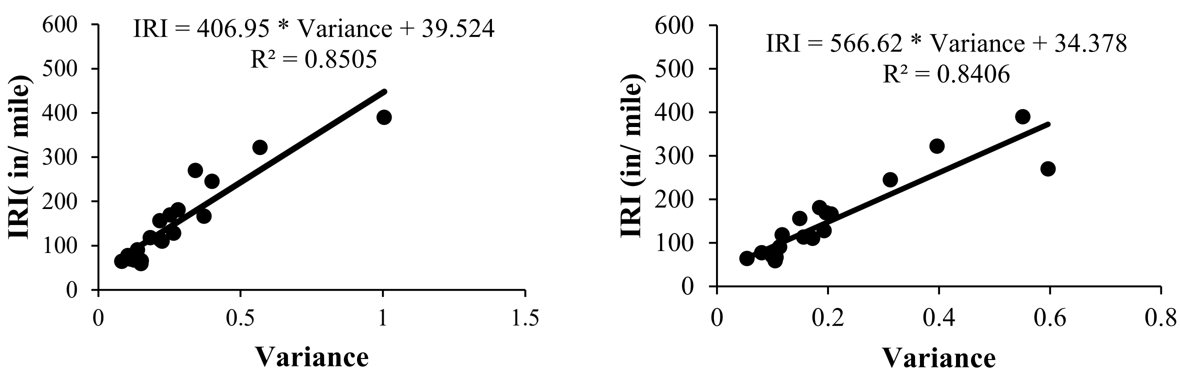


Figure 5.3 Welch Transformation (Using Sony Xperia)

While the previous analyses did not identify useful differences in signal patterns, using variance analysis showed promising results. Figure 5.4 shows a significant linear relationship between the referenced IRI and the variance of the vertical accelerometer measurements using a Samsung Galaxy SIII. The variance results can predict with high significance (R^2=0.85) the referenced IRI values. Also, the results indicate that as the road roughness increases, the variance among the vertical accelerometer measurements will increase, which is a rational reflection of the actual conditions of the road profile.



Variance at 50 mph

Variance at 40 mph

Figure 5.4 IRI vs Variance (Using Samsung Galaxy SIII)

Using regression analysis, two models are developed to predict IRI through the smartphone's accelerometer measurements, as shown in Equations 5.1 and 5.2.

$$IRI(40\ mph) = 566.62 * Var_{40\ mph} + 34.378 \quad (R^2 = 0.84) \quad (5.1)$$

$$IRI\ (50mph) = 406.95 * Var_{50\ mph} + 39.524 \quad (R^2 = 0.85) \quad (5.2)$$

where,
Var is the variance of the accelerometer readings according to Equation (3.2)
IRI is the predicted International Roughness Index (IRI) in inches per mile

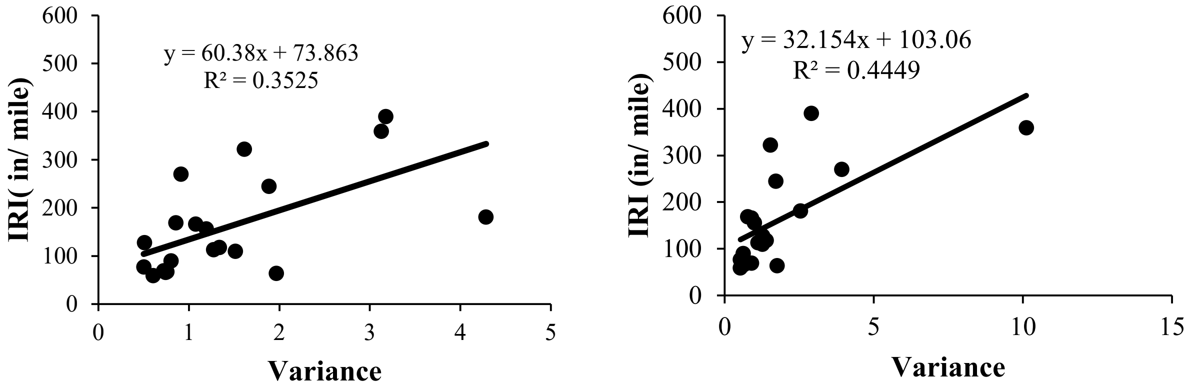
The driving speed seems to affect the way in which the vehicle responds to the road profile (i.e., variance values). In particular, at 50 mph the variances were higher than those measured at 40 mph for all the roadway segments. However, these differences do not detract from the usefulness of the variance to predict the IRI values. The diagnostic plots for verifying Equation 14 and 15 are shown in Appendices A-9 and A-10, respectively.

Consequently, solving Equations 5.1 and 5.2 for the actual IRI thresholds shown in Table 3.2 yields variance thresholds that can be used to directly identify the measured signals, as shown in Table 5.1. Accordingly, these values can be used directly to classify the roadway segments into the different IRI categories.

Table 5.1 IRI Thresholds Using Variances

IRI (Inch/Mile)	Variance Thresholds (40mph)	Variance Thresholds (50mph)
Less than 70	Less than 0.0629	Less than 0.0749
70-100	0.0629-0.1158	0.0749-0.1486
101-130	0.1176-0.1688	0.1511-0.2223
131-170	0.1705-0.2394	0.2248-0.3206
Greater than 170	Greater than 0.2394	Greater than 0.3206

Compared with the signals obtained with the Samsung Galaxy SIII, the measured signals using the Sony Xperia showed an insignificant correlation between the referenced IRI and the variance. The variance values were randomly distributed among the different IRI values. In addition, these variance values were considerably higher than the ones obtained using the Samsung Galaxy SIII. This could most likely be attributed to a lower accuracy of the Sony Xperia's accelerometer compared with the Samsung Galaxy SIII. Hence, using the Sony Xperia in this study could not classify the roadway segments into the different IRI categories. Figure 5.5 shows a plot for the variance values versus IRI using the Sony Xperia at 40 mph and 50 mph.



Variance at 50 mph Variance at 40 mph

Figure 5.5 IRI vs Variance (Using Sony Xperia)

5.2 Validation of the Models

In order to validate the reliability of the variance models (Equations 5.1 and 5.2) in predicting IRI and classifying roadway segments, 15 new segments were selected to perform the experiment again using the Samsung Galaxy SIII. Table 5.2 shows a summary of the statistics for the validation test segments.

Table 5.2 Summary of Validation Test Segments

Number of Test Segments	**Parameter**	**Mean**	**Median**	**Standard Deviation**	**Max**	**Min**
15	IRI	160 in/mile	124 in/mile	83	332 in/mile	57 in/mile
	Length	1.31 mile	1 mile	1.27	5.57 mile	0.3 mile

Figure 5.6 shows the predicted IRI using Equations 14 and 15. It can be noticed that the variance among the accelerometer data is a promising indicator of the actual roughness level. At 50 mph, the predicted IRI of segments 2, 9, 11, and 13 fall outside the actual roughness categories, while the same segments, except 13, fall outside the actual roughness categories at 40 mph. These sections are highlighted in red (outliers). Nevertheless, the t-test results presented in Table 5.3 showed no significant difference between the predicted and the measured IRI values at both speeds.

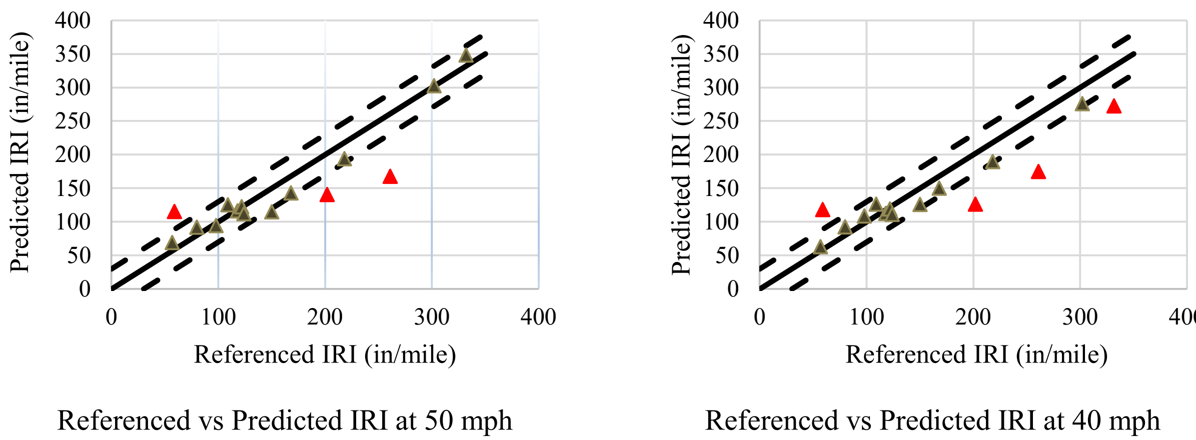


Figure 5.6 Referenced vs Predicted IRI

Table 5.3 T-test Results

Test Parameters	**50 Mph**		**40 Mph**	
	Referenced IRI	**Predicted IRI**	**Referenced IRI**	**Predicted IRI**
Mean	160	151	160	144
Variance	7385.714	6034.369	7385.714	3704.648
Observations	15	15	15	15
Pearson Correlation	0.910		0.925	
Hypothesized Mean Difference	0		0	
df	14		14	
t Stat	1.025		1.602	
P(T<=t) one-tail	0.161		0.0657	
t Critical one-tail	1.761		1.761	
P(T<=t) two-tail	0.323		0.131	
t Critical two-tail	2.145		2.145	

5.3 Chapter Summary

Smartphone vertical accelerometer data were collected using a sedan vehicle. The data were collected using two smartphones, Samsung Galaxy SIII and Sony Xperia A. The time series acceleration data along the z-axis formulate various signals according to the different roughness levels. These signals were then filtered using median and moving average filters to reduce the amount of noise. Different pattern recognition techniques were used to identify the key features among these signals. Regardless of the fact that cross-correlation analysis and Welch periodogram estimates did not show any effectiveness in identifying the measured signals, variance analysis showed promising results. Two models were developed based on the variance of the accelerometer data. These models can predict with high significance the actual roughness (IRI values). Also, it was found that the Xperia's internal accelerometer is not accurate compared with the Samsung. Finally, the difference between the actual IRI and the measured IRI using smartphones was not statistically significant.

6. OPTIMIZATION ANALYSIS

This chapter describes the pavement condition of Wyoming's county roads. In addition, results of optimization modeling are introduced for pavement management and traffic safety management. First, the risk-based analysis and budget optimization results are introduced for the benefit of sensitivity analysis and critical budgets. At the end, the results of optimizing traffic safety countermeasures are included to reduce the crash frequency.

6.1 Risk-Based Optimization Analysis

All variables used in this study, except risk, were collected from field investigation for each roadway segment and then combined in a single database for implementing the optimization model. Risk was calculated using the treatment cost for each roadway segment. The combined dataset contains length of the segment and existing PSI, ADT, and ADTT for each roadway segment. Segment length was used to determine the treatment cost for the whole segment. Existing PSI is the primary variable in the model used to maximize the network average PSI. ADT and ADTT were incorporated to give a higher priority to roadways with higher traffic volumes.

6.1.1 Case Study (Laramie County)

The risk-based optimization considers county roads in Laramie County for analysis. Table 6.1 summarizes data sources with the type and number of units of data collected for the case study. The paved roads were segmented by driving the roads and determining any differences in the pavement types. A total of 17 roads were established. The segments begin and end where there are overlays, new construction, or other changes in the pavement. Each segment was mapped with ArcGIS. The 17 roads included in this study were divided into 23 uniform segments. Traffic counts were obtained on these 23 segments. All the traffic counts were entered into ArcGIS and mapped.

Table **6.1** Features and Data Collected for Laramie County

Feature	**Data source**	**Quantity**	**Units**	**Data types**
County roads	WYDOT	17	Roads	GIS layer of county paved roads
Segmentation	Field	23	Segments	Location of new construction joints
Traffic counts	Field	23	Counts	ADT, ADTT
Pavement performance	Pathway Services, Inc.	23	Segments	IRI, PSI, RUT, PCI, PSR, location

A preliminary descriptive analysis was conducted on the 23 segments to examine variations in the parameters included in the optimization model. The calculated standard deviations of the parameters presented in Table 6.2 show significant variations. This is a confirmation that the selected roads represent the wide variety of Laramie County roads.

Table 6.2 Combined Dataset for Implementing Risk-based PMS model

Variable	**Observation**	**Mean**	**Standard deviation**	**Minimum**	**Maximum**
Length, miles	23	4.5	2.7	1.2	10.7
Existing PSI	23	1.9	1.2	0.0	3.6
Rut depth	23	0.3	0.1	0.2	0.4
ADT	23	150	155	15	518
ADTT	23	34	52	1	243

6.1.2 Data Analysis

The optimization model developed in this research was based on the following principles:

- Preventive and minor rehabilitation treatments are more cost-effective than reconstruction.
- High traffic volume roadways should have higher priority when selecting treatments.
- The only constraint in this model is budget.

In the objective function, annual budget was determined by the cost of a single project applying the most expensive treatment. From the data used in this research, it was found that Black Hills Road costs $12.12 million for implementing a 5-R construction treatment. Therefore, $13 million was considered as the budget limit.

To optimize the available budget, different counties might be interested in optimizing different parameters. For example, engineers might want to maximize the average expected PSI. In this research, the following five possible options were analyzed to demonstrate to counties the potential of the proposed optimization:

- Option 1: Maximizing weighted expected PSI
- Option 2: Minimizing weighted expected risk
- Option 3: Maximizing ADT
- Option 4: Maximizing ADTT
- Option 5: Combining the above four options

In Table 6.3, results of the five optimization models are presented. In the roadway network, segments are different in length, traffic volume, and pavement condition. When results were summarized for different models, the variables were weighted based on length to compare among different model options. For all the options, budget was limited to $13 million. In the table, it can be seen that for each option, the results of objective function appear in bold type. For example, option 1 maximized weighted expected PSI, which is 2.11. The results of other parameters (ADT, ADTT, and risk) were also presented to compare with other options. Among the options, option 5 provides the maximum benefit to society by optimizing PSI, risk, ADT, and ADTT.

Table 6.3 Summary Results Optimizing Different Objective Functions with a Budget Of $13 Million.

Optimization	**Objective function**	**Weighted expected**	**Average PSI**	**Weighted ADT**	**Weighted ADTT**	**Expected weighted risk with treatment**	**Budget**
Option 1	Maximizing weighted expected PSI	**2.11**	0	26	36	0.11	$12,905,000
Option 2	Minimizing weighted expected risk	2.02	0	23	32	**0.09**	$12,998,000
Option 3	Maximizing ADT	2.11	0	**26**	36	0.11	$12,905,000
Option 4	Maximizing ADTT	2.03	3	21	**43**	0.20	$12,990,000
Option 5	Maximizing weighted expected PSI, ADT and ADTT with minimum risk	2.01	0	24	34	0.10	$12,9473,000

As option 5 provides the maximum benefit to society, this model is used to analyze the following three possible scenarios to show the potential of this model:

1) Selecting projects with a certain budget limit.
2) Improving the weighted average PSI from existing conditions to good conditions. In this research, good conditions were defined as a weighted average PSI above 3.0.
3) Keeping the same weighted average PSI next year as it is now.

Table 6.4 provides a summary of the first scenario with a budget of $13 million. In this table, the summary of selected projects appears in bold type. Similarly, the second and third scenarios select the segments that cost approximately $40.9 and $5.1 million, respectively.

Table 6.4 Selected Projects for Next Year Using Option 5 with a $13 Million Budget

Segment ID	Road Name	Length	Existing PSI	Existing Rut Depth	Treatment Type	ADT	ADTT	Estimated Cost	Expected PSI with treatment within budget
222-1	Chalk Bluff Road/"78" Rd	6.1	0.3	0.3	GM	168	72	-	0.00
3	Albin/LaGrange Rd	10.7	0.9	0.295	GM	108	22	-	0.19
6	Black hills Rd	10.1	0.1	0.322	GM	114	36	-	0.00
19-1	Old Highway Birns West	6.5	0.3	0.359	GM	198	26	-	0.00
222	Chalk Bluff Road/"78" Rd	5.5	1	0.296	GM	168	72	-	0.41
21-2	Old Yellowstone Rd	2.7	0.2	0.319	GM	36	6	-	0.00
21-1	Old Yellowstone Rd	1.9	0.9	0.241	GM	36	6	-	0.19
21	Old Yellowstone Rd	1.2	0	0.328	GM	36	6	-	0.00
10	**Chalk Bluff Road/"78" Rd**	**7.7**	**1.4**	**0.377**	**4-R**	**350**	**40**	**$5,005,000**	**4.10**
18-1	Moffet Rd	4.5	1.3	0.308	GM	26	1	-	0.96
15	**Hillslade Rd West**	**3.8**	**2.2**	**0.157**	**3-R**	**372**	**62**	**$1,330,000**	**4.00**
14-1	**Hillslade N Rd/Midway**	**5.1**	**2.8**	**0.275**	**3-R**	**372**	**62**	**$1,785,000**	**4.00**
13	**Gillaspie Rd**	**4.8**	**2.8**	**0.272**	**3-R**	**37**	**7**	**$1,680,000**	**4.00**
18	Moffet Rd	3.5	3.1	0.228	GM	26	1	-	2.98
2	**A-118-1**	**2**	**3.2**	**0.277**	**3-R**	**34**	**7**	**$700,000**	**4.00**
11	**Chalk Hill/Bliss Rd**	**2**	**3.2**	**0.264**	**3-R**	**34**	**7**	**$700,000**	**4.00**
7	**Bristol Ridge/Hirsig Rd**	**1.6**	**2.9**	**0.208**	**3-R**	**31**	**1**	**$560,000**	**4.00**
8	**Bruegman Rd**	**1.3**	**2.9**	**0.26**	**3-R**	**24**	**4**	**$455,000**	**4.00**
1	**CR 140-1**	**4.3**	**2.4**	**0.219**	**1-R**	**328**	**40**	**$258,000**	**3.90**
5	Bear Creek/marsh Rd	2.7	2.1	0.26	GM	15	1	-	1.99
9	Carpenter Rd/Berger Rd	2.5	3.1	0.193	GM	518	243	-	2.98
14	Hillslade N Rd/Midway	8.1	3.5	0.216	GM	372	62	-	3.40
21-3	Old Yellowstone Rd	4.9	3.6	0.154	GM	36	6	-	3.51
Average			1.71						2.01
Total		103.5						$12,473,000	

6.1.3 Sensitivity Analysis

Engineers must know the appropriate budget providing the maximum benefit to society. The appropriate budget has been determined based on the four performance parameters: weighted PSI, weighted rut depth, weighted ADT, and ADTT. The option 5 model has also been implemented here. Figure 6.1 shows the trends of the performance parameters as the budget increases.

For identifying the appropriate budget, the slope of the performance curves is critical. Figure 6.1 shows that the slope of the rut depth curve from $3 to $12 million is higher than it is from $12 to $24 million. Therefore, $12 million is the appropriate budget. Similarly, the trends of weighted PSI and weighted ADT and ADTT have been analyzed and show that $12 million is the most appropriate budget (Figure 6.1).

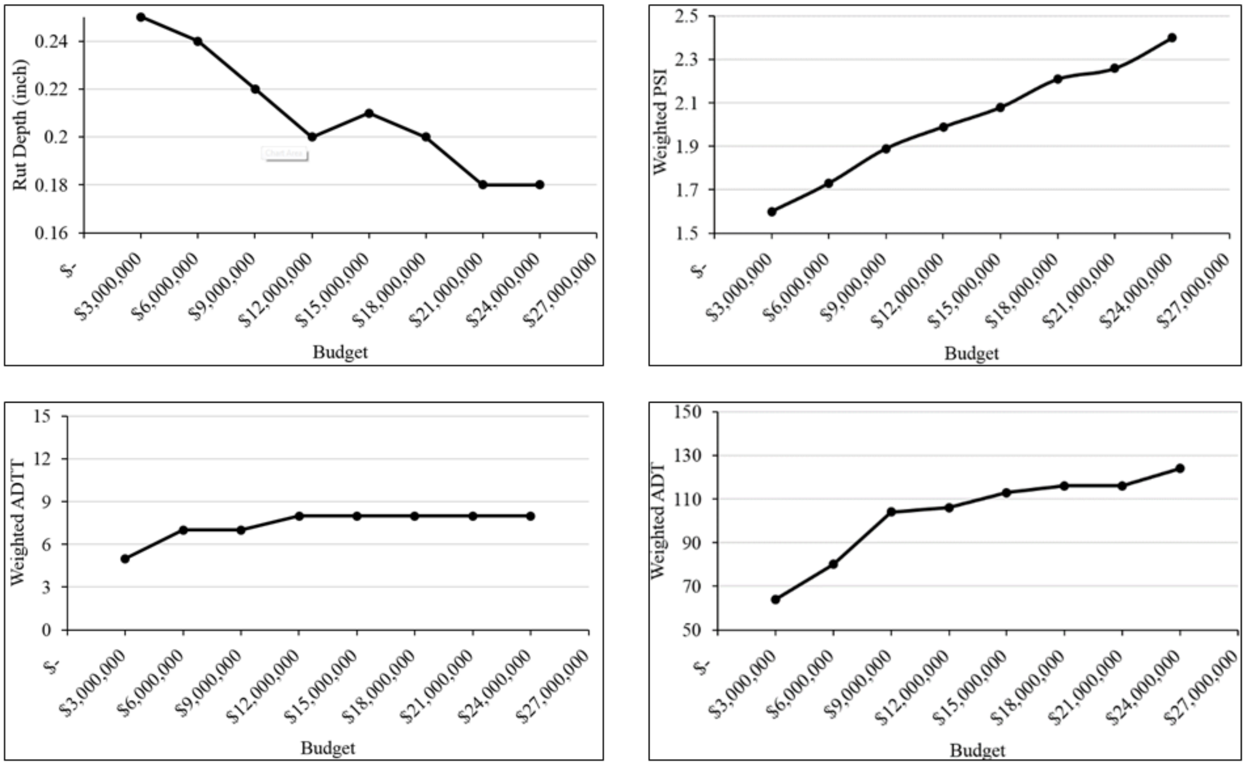


Figure 6.1 PMS Performance Parameters Comparison for Different Budgets

6.1.4 Five-Year Capital Improvement Plan

A capital improvement plan (CIP) is a road map for counties that provides direction and guidelines to carefully plan and manage their capital and roads. This model can also be implemented to develop a CIP. As a case study, the option 5 model has been implemented to develop a five-year CIP.

It is assumed that in five years the weighted average PSI is expected to increase from existing conditions to 3.25. To achieve this goal, engineers may want to know how much funding should be requested. To do this analysis, every year the PSI and rut depth of each segment were predicted based on the performance curves provided by WYDOT. It was also assumed that narrow roads (road width of 26 feet) need to be widened to at least 30 feet in the first treatment in five years. Considering all of these conditions, the option 5 model has been implemented to develop a five-year CIP. Table 6.5 shows the summary results indicating how much money needs to be requested every year to achieve the goal in five years. It can be seen that for every year, except year five, approximately $12.5 million is required. Year five requires only $7.8 million to achieve the goal. Table 6-6 presents the list of treatments every year. The table shows that when a treatment is applied on a specific road, for next few years only GM is required, which is as expected.

Table 6.5 Five-year Spending Plan with a $13 Million per Year Budget

	Budget	**Weighted PSI**	**Weighted rut depth (inches)**	**ADT**	**ADTT**
Existing		1.71	0.28	45	11
Year 1	$12,473,000	2.01	0.20	106	8
Year 2	$12,473,000	2.35	0.16	131	18
Year 3	$111,280,000	2.68	0.14	141	23
Year 4	$12,120,000	3.05	0.12	152	26
Year 5	$7,800,000	3.26	0.10	135	26

Table 6.6 Selected Projects for Next 5 Years with a $13 Million per Year Budget

Segment ID	**Road Name**	**Year 1**	**Year 2**	**Year 3**	**Year 4**	**Year 5**
222-1	Chalk Bluff Road/"78" Rd	GM	**5-R**	GM	GM	GM
3	Albin/LaGrange Rd	GM	GM	GM	GM	GM
6	Black hills Rd	GM	GM	GM	**5-R**	GM
19-1	Old Highway Birns West	GM	GM	GM	GM	**5-R**
222	Chalk Bluff Road/"78" Rd	GM	GM	**5-R**	GM	GM
21-2	Old Yellowstone Rd	GM	GM	**5-R**	GM	GM
21-1	Old Yellowstone Rd	GM	**5-R**	GM	GM	GM
21	Old Yellowstone Rd	GM	GM	**5-R**	GM	GM
10	Chalk Bluff Road/"78" Rd	**4-R**	GM	GM	GM	GM
18-1	Moffet Rd	GM	GM	GM	GM	GM
15	Hillslade Rd West	**3-R**	GM	GM	GM	GM
14-1	Hillslade N Rd/Midway	**3-R**	GM	GM	GM	GM
13	Gillaspie Rd	**3-R**	GM	GM	GM	GM
18	Moffet Rd	GM	**3-R**	GM	GM	GM
2	A-118-1	**3-R**	GM	GM	GM	GM
11	Chalk Hill/Bliss Rd	**3-R**	GM	GM	GM	GM
7	Bristol Ridge/Hirsig Rd	**3-R**	GM	GM	GM	GM
8	Bruegman Rd	**3-R**	GM	GM	GM	GM
1	CR 140-1	**1-R**	GM	GM	GM	GM
5	Bear Creek/marsh Rd	GM	**4-R**	GM	GM	GM
9	Carpenter Rd/Berger Rd	GM	**1-R**	GM	GM	GM
14	Hillslade N Rd/Midway	GM	GM	GM	GM	GM
21-3	Old Yellowstone Rd	GM	GM	GM	GM	GM

6.2 Optimizing Maintenance Budgets

Similar to risk-based analysis, all variables used in this study, except cost-factor, were collected from field investigation for each roadway segment and then combined in a comprehensive database for implementing the optimization model. Cost-factor was calculated using the treatment cost for each roadway segment. The combined dataset contains length of the segment, IRI, rut, PCI, existing PSI, ADT, and road width for each roadway segment. A preliminary analysis was conducted on the datasets used in this task to examine potential factors related to the optimization model, such as average network rut depth, IRI, PCI, PSI, and cost-factor.

6.2.1 Preliminary Analysis (Statewide County Paved Roads)

In Wyoming, as shown in Table 6.7, there are 917 county paved roads with a total length of 2,444 miles. These 917 roads are divided into 2,250 uniform roadway segments. A preliminary analysis was conducted on the datasets used in this research to examine potential factors related to the optimization model, such as average network rut depth, IRI, PCI, PSI, and risk. Of the 2,250 roadway segments, 85 had a missing pavement condition parameter. These 85 segments were not included in the optimization model.

Table 6.7 Summary of Statewide County Paved Roads

	Statewide County Paved Roads
Total Length, miles	2,444
Total Number of Roads	917
Total Number of Segments	2,250
Minimum Segment Length, mile	0.01
Maximum Segment Length, mile	30.8

Pavement condition parameters used in the optimization model are summarized in Table 6.8. A total of 881 county paved roads with 2,339 miles divided into 2,167 roadway segments were used to summarize rut depth, IRI, PCI, PSI, and risk. According to the classification of road condition parameters from a report by Saha and Ksaibati (Saha & Ksaibati, 2015), the overall pavement condition denoted by PSI is very poor.

Table 6.8 Summary of Existing Road Conditions

Average Weighted Parameters	**Minimum**	**Maximum**	**St. Deviation**
Rut Depth, inches	0.05	0.71	0.08
International Roughness Index (IRI)	46	2144	216
Pavement Condition Index (PCI)	4	100	15
Pavement Serviceability Index (PSI)	0	3.96	0.99

According to the existing pavement conditions, county paved roads are in need of significant maintenance. If all the roadway segments are maintained as required, the PSI will increase to 4.12, which will cost $1.5 billion. On the other hand, if the roadway segments are not maintained at all, PSI will decrease from 1.43 (existing condition) to 1.18. The data analysis section will identify the minimum best budget providing the most benefit to society. Figure 6.2 shows the total length of each treatment type. It can be seen that most of the segments require 5-R treatment type (complete replacement), and total cost for that is $1.1 billion.

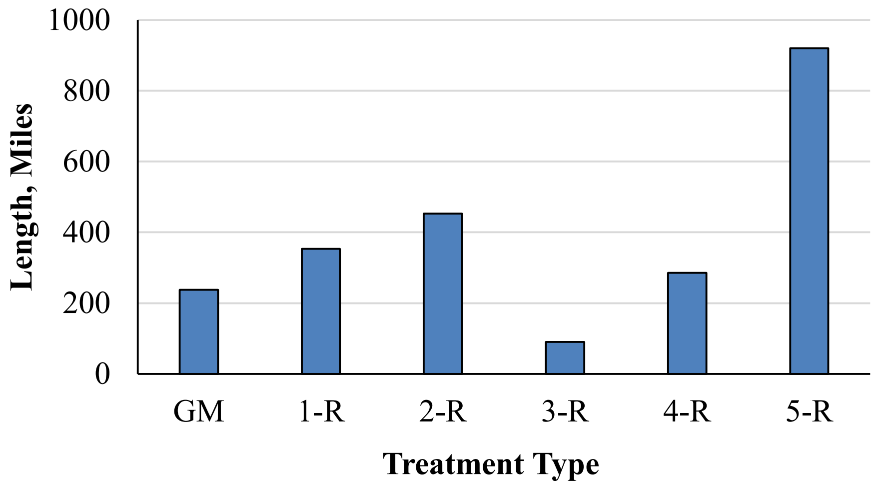


Figure 6.2 Treatment Summary of County Roads by Road Length

6.2.2 Data Analysis

The optimization model developed in this research was based on the following principles:

- Preventative and minor rehabilitation treatments are more cost effective than reconstruction
- Higher functional classification of roadways should have higher priority when selecting treatments.

In order to optimize the budget, different counties might be interested in optimizing different parameters. For example, engineers might want to maximize the average expected PSI. Saha and Ksaibati (Saha & Ksaibati, 2015) concluded that the combination model incorporating PSI, cost-factor, and functional class of roadways provides the most benefit to society. In this research, only the combination model was implemented.

To validate the first principle mentioned above, a data analysis was conducted to determine where to invest budget dollars that provide the maximum benefits to society (see section Assignment of Funds).

6.2.2.1 Assignment of Funds

In this section, all the roadway segments were divided into three categories: just before start of rapid deterioration, rapidly deterioration, and worst case. Different funding levels were allocated to these three categories. The analysis found that investment on the "just before start of rapid deterioration" provides maximum benefits to society. In other words, applying preventive and minor rehabilitation treatments in a timely manner is more cost effective than letting pavement sections deteriorate and then having to reconstruct them.

Before implementing the optimization model, it is important to assign the funds available to pavement segments with three deterioration levels:

(1) Just before start of rapid deterioration.
(2) Rapidly deterioration.
(3) Worst case.

As preventative and minor rehabilitation treatments get the priority over major rehabilitation in this model, only 15% of the funds were assigned to treat the segments that needed 4-R and 5-R. Similarly, 25% and 60% of available funds were assigned to rapidly and before rapidly deteriorating segments, respectively. Table 6.9 shows the effectiveness of allocated funding for each deterioration level. For each deterioration level, the change of PSI per $1 million of spending was calculated for different budgets. The last column of Table 6.9 shows the average change of PSI per million dollars of spending at different deterioration levels. It can be seen that the "just before start of rapid deterioration" category provides 2.14 times more benefits in terms of increasing overall PSI compared with "rapidly deteriorating" segments. The average change of PSI for "worst case" is negative, which indicates that the increase of PSI for the segments getting treated is less than the decrease of PSI on other segments not getting treated. From this analysis, it can be concluded that investing total funding on the segments in the "before rapid deterioration" category is the most cost effective. Any leftover funding can be then invested in "rapidly deteriorating" segments. Anything remaining can be invested in segments in the "worst case" deterioration category.

6.2.2.2 Efficient Budget Determination

Using the percentage of funds assigned to each deterioration category, the network PSI were calculated at different budget scenarios, as shown in Figure 6.3. For identifying the appropriate budget, the slope of the performance curve is critical. Figure 6.3 shows the slope of the PSI from $5 to $25 million is higher than it is from $25 to $60 million. Therefore, $25 million is the appropriate budget.

Table 6.9 Effectiveness of Funds Assigned to Various Deterioration Levels

Deterioration Category	Budget, Million	Existing PSI	1st Year PSI	Change of PSI per Million Dollar	Average Change of PSI per Million Dollar
Before Rapid	$5.87	2.75	3.02	0.046	0.045
	$8.98	2.75	3.149	0.044	
	$10.98	2.75	3.239	0.045	
	$14.92	2.75	3.415	0.045	
	$17.97	2.75	3.538	0.044	
	$21.20	2.75	3.686	0.044	
Rapid	$2.07	1.386	1.431	0.022	0.021
	$3.45	1.386	1.463	0.022	
	$5.20	1.386	1.494	0.021	
	$6.24	1.386	1.52	0.021	
	$7.50	1.386	1.544	0.021	
	$8.72	1.386	1.57	0.021	
	$12.77	1.386	1.647	0.020	
	$16.65	1.386	1.73	0.021	
	$21.15	1.386	1.831	0.021	
	$42.54	1.386	2.28	0.021	
	$62.75	1.386	2.71	0.021	
Worst	$1.31	0.844	0.324	-0.396	-0.123
	$2.63	0.844	0.328	-0.196	
	$3.54	0.844	0.332	-0.145	
	$4.27	0.844	0.335	-0.119	
	$4.93	0.844	0.337	-0.103	
	$5.58	0.844	0.339	-0.091	
	$5.89	0.844	0.34	-0.086	
	$6.37	0.844	0.342	-0.079	
	$7.48	0.844	0.346	-0.067	
	$11.20	0.844	0.36	-0.043	
	$15.00	0.844	0.375	-0.031	

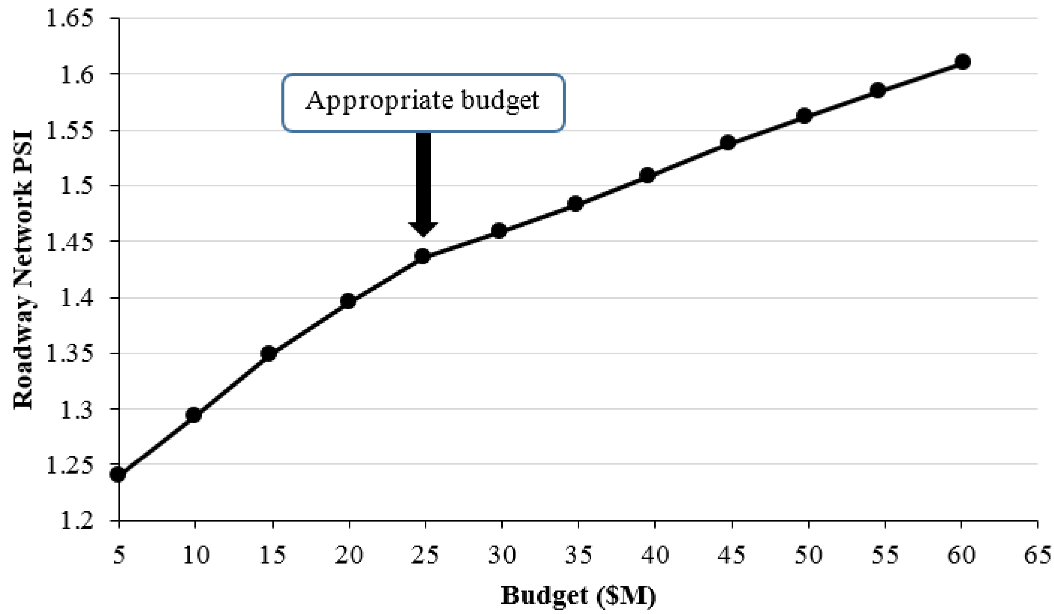


Figure 6.3 Network PSI Comparison for Different Budgets

6.2.3 Five-Year Capital Improvement Plan

A capital improvement plan (CIP) is a roadmap for local governments that provides the budget needs over five years. The developed model was utilized to develop a CIP in this study. Because $25 million was determined as the appropriate budget, it was considered that a per-year average of $25 million of funding is assigned to maintain county roads. The PSI of each segment was predicted based on the performance curves. It was assumed that narrow roads (road width < 7.93 meters) need to be widened to at least 9.15 meters in the first treatment in five years. Considering all of these conditions, the model was implemented to develop a five-year CIP. It was found that for every year, except year two, approximately $25 million is required. Year two requires $29.5 million to maintain existing conditions. Table 6.10 presents an example of treatments listed every year. The table shows that when a treatment is applied on a specific road, for next few years only GM is required, which is as expected.

Table 6.10 Example Projects for Next Five Years with a $25 Million per Year Budget

Segment ID	Road Name	Year 1	Year 2	Year 3	Year 4	Year 5
222-1	Chalk Bluff Road/"78" Rd	GM	**1-R**	GM	GM	GM
3	Albin/LaGrange Rd	GM	GM	GM	GM	GM
6	Black hills Rd	GM	GM	GM	**1-R**	GM
19-1	Old Highway Birns West	GM	GM	GM	GM	**1-R**
222	Chalk Bluff Road/"78" Rd	GM	GM	**1-R**	GM	GM

6.3 Critical Budget for Traffic Safety Management

The following two principles were considered to develop the optimization model of TSMS:

(1) Countermeasures expected to reduce crashes to a greater extent at lower cost are the most cost-effective.
(2) Roadway segments with higher traffic should have higher priority than roads with lower traffic when selecting treatments.

Crash data are important for developing the TSMS. This study obtained crash data from 2010 to 2014 from WYDOT in an Excel spreadsheet. In the spreadsheet, each crash contained information related to driver, roadway, and vehicle. Of this information, only milepost and route number were used in this study.

Before implementing the optimization model, crash hot spots had to be identified. In this research, the EB method was implemented to identify the crash hot spots. The expected crashes were estimated using the safety performance function of two-lane two-way roadways obtained from the Highway Safety Manual (AASHTO, 2010). An SPF is an equation used to predict the average number of crashes per year at a specific location as a function of different variables, including traffic counts and roadway geometry. A total of 41 crash hot spots were identified among 3,762 segments, each of which was a maximum of one mile in length.

Decision makers need to allocate critical funding to provide the maximum benefit to society. This study determined the critical budget based on the expected crash reduction. Optimization was performed at various budgets levels between $100,000 and $800,000. Figure 6.4 shows the trend in the reduction of expected crashes as the budget increases. The slope of the estimated crash reduction between $100,000 and $275,000 is higher than that between $275,000 and $800,000. Therefore, $275,000 is the critical budget level based on the assumptions made when running the optimization model.

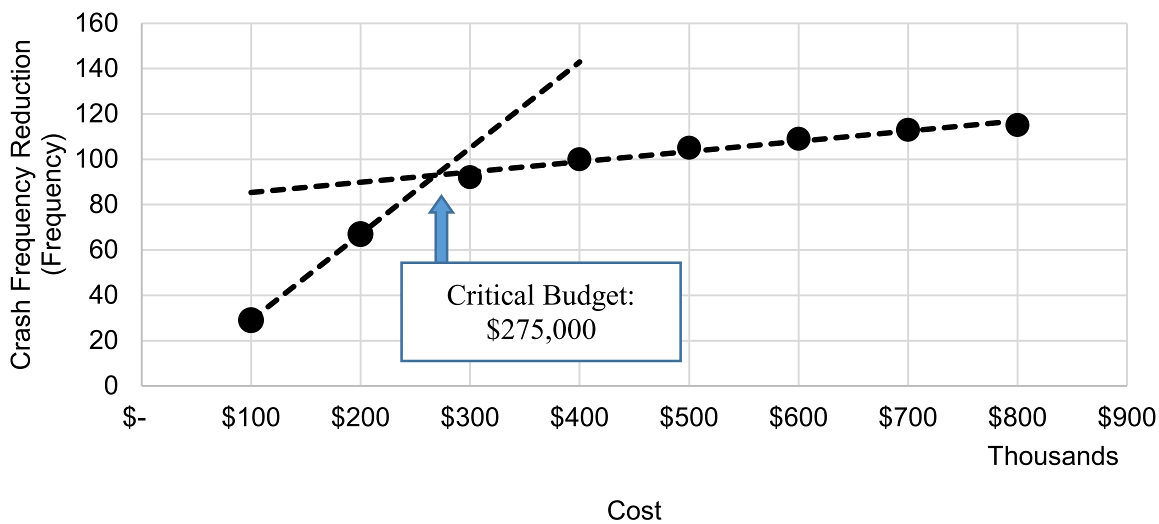


Figure 6.4 TSMS Performance for Different Budgets

6.4 Chapter Summary

This chapter applies multiple optimization models to maximize the overall performance of county paved roads in Wyoming. Using a case study of Laramie County, the optimization results show the risk-based consideration of pavement maintenance considering an annual budget constraint of $13,000,000. A five-year capital improvement plan was developed for county roads considering the most beneficial scenario to society. In addition, maintenance budgets were optimized considering cost factors. The results show that applying preventative and minor rehabilitation treatments in a timely manner is more cost effective than letting pavement sections deteriorate and then reconstructing them. By considering this maintenance scenario, the critical budgets were defined and constrained along a five-year capital improvement plan for county paved roads.

Furthermore, the cash-reduction-based optimization analysis provides the best set of road preservations and countermeasures to reduce future crash frequency of crash hotspots. Using the safety performance functions developed in the Highway Safety Manual, future crashes can be projected to determine crash reduction factors. The multiple analysis defines the critical budgets within the traffic safety management for county paved roads.

7. CONCLUSIONS AND RECOMMENDATIONS

This study deals with four main issues related to Wyoming county roads management. These issues are the county roads serviceability prediction; the cost of measuring pavement roughness; the optimization modeling for pavement management; and optimization analysis for traffic safety management. Two experiments were designed to develop data-driven performance models in terms of pavement serviceability index (PSI) and international roughness index (IRI). In addition, the developed optimization models define the best set of road maintenance projects for pavement and traffic safety countermeasures. The main conclusions and outcomes of this research are presented in the following subsections.

7.1 Serviceability Prediction Models

A riding quality survey was conducted to develop new serviceability prediction models suitable for county roads. The State of Wyoming does not currently have a model to predict the pavement serviceability rating of county paved roads. In this study, a PSI model was developed for county paved roads based on the perceptions of Wyoming residents. The newly developed model was statistically valid and may provide better representation of county road conditions, compared with the Wyoming statewide model. The main conclusions drawn from this study are:

- The mean panel ratings (MPR) of local county roads can be predicted reasonably from the wide range of roadway distresses.
- The seating position, age, and gender of the rater are not significant factors, while vehicle's type is significant in the rating process.
- Using sedan vehicles is more preferable than SUVs in conducting riding quality surveys, especially when it comes to rehabilitation analysis purposes.
- Equation 11 can be used to predict with high certainty the PSR values for Wyoming county roads to identify maintenance and various rehabilitation needs.
- PSI is a subjective parameter affected by different experimental factors (i.e., vehicle type, vehicle speed). However, it surpasses the solely objective parameters assessment (i.e., IRI and PCI) by considering the driving public's perceptions. This difference is crucial when it comes to the maintenance and rehabilitation selection process.
- Wyoming drivers have lower expectations when it comes to the ride quality of roads at the local system compared with the statewide system.
- In general, the WYDOT Model (Equation 1) gives lower PSR values for county roads when compared with a higher roadway classification, which can be misrepresented in the PMS process of county roads.

7.2 Roughness Measurements Using Smart Phones

As a cost effective solution, the ability of modern smartphones in returning reliable IRI measurements as part of PMS was evaluated. Using MATLAB, simple signal processing and pattern recognition techniques were applied in order to identify useful features of various signals measured using smartphones. The signal features were compared to referenced IRI values, which were measured using a standard profiler (South Dakota profiler). Two models were developed with high correlation to directly predict the IRI through smartphone measurements. The difference between the predicted and the measured IRI was not statistically significant. The main conclusions drawn from this study are as follows:

- The measured signals (time series acceleration data) using smartphone accelerometers are highly similar in shape. The actual IRI values do not affect the shape of the measured signals significantly.

- Smartphone-measured signals have approximately the same energy at various frequencies (i.e., PSD) within the different IRI levels.
- The type of smartphones used seems to be a significant factor in measuring the roughness of roadway profiles.
- Using a Samsung Galaxy SIII, the variance among the vertical accelerometer measurements can, with high certainty, classify the measured signals within the different IRI categories. However, a few segments were classified outside the designated IRI category.
- Equations 14 and 15 can be used with high certainty to predict the actual IRI values. The t-test results show that the difference between the measured and the predicted IRI is not significant.
- The calculated variance values are speed dependent. However, the speed does not affect the usefulness of variance in predicting IRI. In addition, the variance values are higher at 50 mph.
- The observed results confirm the ability of smartphones in returning acceptable IRI results compared with a standard profiler. These results are comparable with the previous conducted studies in this field. However, the simplicity of data analysis used in this study is very important when it comes to automation of the data collection process.

7.3 Risk-Based Optimization Analysis for Pavement Management

In this study, a risk-based methodology was developed to identify the best mix of road preservation projects that use limited available resources. The developed methodology was implemented in a small county road network consisting of 17 roads divided into 23 segments totaling 103.5 miles. This methodology optimized overall expected PSI, traffic and truck traffic, and risk by selecting the best mix of road preservation projects. Using a case study of Laramie County, various analysis scenarios were examined using the proposed model including selecting projects for the next five years considering a limited budget, allocating variable annual budgets for five years to maintain a certain PSI, determining minimum budget to maintain existing PSI, and determining budget to provide maximum benefit to society. The developed methodology can be highlighted as follows:

- It is tailored specifically to county paved roads.
- As FHWA requires incorporation of risk into PMS, this methodology includes risks related to minimizing life-cycle cost, increasing traffic and truck loading, and budget constraints.
- This methodology is flexible to analyze different scenarios, such as developing a five-year CIP within a limited budget, determining minimum budget to keep existing conditions, and to provide maximum benefit to society.
- This methodology can be implemented in all 23 Wyoming counties and can be used by other states for developing a PMS for county roads.

7.4 Optimizing Budgets for Statewide Pavement Management

An innovative optimization methodology was developed in this study to be used to manage local roads. The following aspects of the developed methodology investigated in this study are not completely explored in previous research:

- Since the legislators in Wyoming are interested in allocating funding for all county paved roads, a statewide optimization was conducted to identify the budget needs for all local roads.
- It is important for county engineers to know that preventive and minor rehabilitation treatments are very cost effective. This study conducted a data analysis confirming that preventive and minor rehabilitation are very cost effective on county roads.
- Since statewide traffic data were not available for county paved roads, functional classification of roadways were utilized in the optimization.
- The developed methodology includes cost factors related to minimizing life-cycle cost and increasing the weight factors on county roads with heavier traffic loadings.

- This methodology is flexible to analyze different scenarios, such as developing a five-year capital improvement plan within a limited budget, determining minimum budget to keep existing condition, or to provide maximum benefit to society.

7.5 Optimizing Traffic Safety Management

Decision makers and engineers need to know the critical budget for PMS and TSMS to allocate budgets for different agencies. This research developed an optimization methodology for PMS and a crash-reduction-factor–based optimization methodology for TSMS to identify the best set of road preservation and safety improvement projects, respectively. Using these methodologies, a sensitivity analysis was conducted to determine the critical budgets. The following conclusions are made about the developed methodology for PMS and TSMS:

- The developed methodology can be implemented specifically on county paved roads.
- This methodology includes a cost factor related to minimizing life-cycle costs to maintain roads and improve safety efficiently.
- The PMS and TSMS consider different types of data, including functional classification of roadways, safety effectiveness of countermeasures such as CRF, and improvement costs.
- The PMS and TSMS provide a higher priority to projects on roadway segments with higher ADTs.
- The models identify critical budgets needed to provide maximum benefits to society by improving road conditions and reducing crashes.
- This methodology can be implemented by other states to develop PMS and TSMS for various roadway networks.

7.6 Recommendations

- It is recommended to use the newly developed PSI model in the county road PMS. However, when comparing county road conditions with the state's highway system, the state model should be used for both county and state roads.
- The new PSI model of county roads provides a more focused description of the actual rehabilitation needs of the county roads network. This way, the new model will be more suitable for selecting new projects. However, when it comes to presenting the status of county roads to legislators, the WYDOT model should be used. Hence, better funding opportunities can be secured. The methodology developed and implemented in this research can be implemented in other states with minor changes.
- Smartphone applications can be developed easily to return the predicted IRI directly. Nevertheless, further investigations are required to address different variables that may affect the IRI measurement using smartphones. For example, the test can be performed using different types of smartphones, vehicles, and lower speeds. The ability to measure IRI at low speeds (i.e., 30 mph) will be essential to traffic safety, especially in residential areas.
- In order to secure appropriate funding from the Wyoming Legislature to implement a statewide county PMS, it is recommended that the proposed risk-based pavement management model be implemented. This model is based on the current conditions of the road maximizing the expected average PSI and ADT with minimum risk associated with the future maintenance cost.
- It is recommended that additional sources of data, such as previous maintenance records, highs and lows of estimated cost for each treatment type, and pavement conditions, be incorporated in the optimization in the future to increase the accuracy of the results. To calculate risk, there are some other factors besides life-cycle costs. The variation of maintenance costs, such as climate, soil conditions, traffic, and impact of the oil and gas industry needed to be incorporated into the optimization model.

- It is important to note that the objective function used in this model considered the parameters that may not be important to other states. For example, in the case study, truck traffic was incorporated to consider the impact of the oil and gas industry. For other states, this parameter may not be as important. In this regard, some minor changes in the methodology may be needed to reflect local conditions in other states.

7.7 Future Research

- The ability of smartphones in evaluating county road conditions should be investigated in depth. Different combinations of vehicles, smartphones, and driving speeds must be used. This would allow a comprehensive evaluation of all variables that influence the evaluation process using smartphones. Moreover, an investigation should be performed to evaluate a smartphone's ability to predict driving public perceptions (PSI). This may present a cost effective solution to estimate the PSI of county roads directly without the reliance on roadway condition indices.
- A statewide optimization analysis can be executed to provide statewide implementation plans along a predefined analysis period. The multi-year maintenance plans would aim at achieving a specific performance target and within specific maintenance policies and budget levels.

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APPENDICES

Appendix A-1: Rater Instruction and Training Session

One day prior to the rating day, raters were given detailed instructions on the riding quality survey as follows, most of these instructions were adapted from the previous literature (Nakamura 1962, Nair, et al. 1985, ASTM E1927-98):

1. You will be given a defined seating position that must remain the same during the entire study period.
2. A designated driver will take you to a number of roadway segments in Cheyenne. Then, you are requested to rate these segments based on your comfortability only. Your rating should reflect how well the quality of ride that you experienced only.
3. The rating scale ranges from 0 for worst ride quality and 5 for best ride quality. Before the driver reaches to a specific roadway segment, a study member will hand you a rating form with your name and a specific serial number (a copy of the rating form is shown to the raters before conducting the study). You are requested to put a tick mark on the scale shown on the rating form. Your marking should reflect the degree of your comfortability only.
4. Once you reached the required segment, a study member will inform everyone by saying “Rating Starts”. The same member will inform you when the ride over the segment is about to finish by saying “Rating Ends”.
5. We want you to concentrate on how you feel while riding over the test segment and provide rating accordingly. Don’t let the appearance of the road to deceive you.
6. Keep your rating for yourself, don’t share your ride experience with the other raters. Cheating is not allowed as we don’t have wrong or right answers, just reveal your riding quality experience on the shown scale.
7. At the bottom of the rating form, we left 2 lines space. Please feel free to share with us any comments that you do believe that it may help us in assessing the quality of ride. For example, if the testing vehicle slowed down due to an interruption from the neighboring traffic.
8. We have included few words to describe the rating scale (i.e. fair or good). Try to use these words to help you during the rating process.

The training session was conducted in the morning of the rating day. The raters were taken to a specific roadway segments (usually 3 segments) with a known pavement roughness. After the end of the rating process of these segments. The obtained ratings were discussed in line with actual conditions of the rated segments. This way the raters can build the required sense of feeling the roads roughness.

Appendix A-2: List of roadway segments that were used in the riding quality survey (SUV vehicle)

SN	COUNTY	Route	BegMP	EndMP	Primary Name	Rut	IRI	PCI	Length(miles)
L1	Laramie	ML6749B	0.40	1.11	129-1	0.07	128	89	0.71
L2	Laramie	ML7428B	0.00	0.47	HR Ranch Road	0.15	149	89	0.47
L3	Laramie	ML6868B	1.00	1.46	Allison Road U4056	0.18	161	100	0.46
L4	Laramie	ML6856B	2.75	3.16	Chalk Bluff/"78" Road	0.30	202	72	0.41
L5	Laramie	ML9382B	5.75	7.61	124-2	0.40	218	62	1.86
L6	Laramie	ML6895B	0.00	1.00	Old Highway Burns West	0.49	261	52	1.00
L7	Laramie	ML6856B	17.57	18.58	Chalk Bluff/"78" Road	0.12	59	100	1.01
L8	Laramie	ML6856B	23.98	24.24	Chalk Bluff/"78" Road	0.12	65	96	0.26
L9	Laramie	ML6875B	5.09	6.49	209-2	0.12	70	86	1.40
L10	Laramie	ML6774B	10.13	12.14	Hillsdale North Road/Midway	0.11	77	97	2.01
L11	Laramie	ML6749B	1.97	2.23	129-1	0.1	85	83	0.26
L12	Laramie	ML6875B	8.81	11.15	209-2	0.13	91	95	2.34
L13	Laramie	ML6744B	3.39	3.64	Avenue C U4019	0.09	114	90	0.25
L14	Laramie	ML6749B	0.40	1.11	129-1	0.07	128	89	0.71
L15	Laramie	ML6856B	3.16	7.25	Chalk Bluff/"78" Road	0.25	151	57	4.09
L16	Laramie	ML6743B	1.80	2.09	125-2	0.15	139	83	0.29
L17	Laramie	ML6921B	2.85	3.07	Ridley Road	0.13	172	85	0.22
L18	Laramie	ML6867B	0.10	0.65	Prosser Road	0.24	322	76	0.55
L19	Laramie	ML6895B	3.02	5.03	Old Highway Burns West	0.23	245	62	2.01
L20	Laramie	ML7155B	0.25	0.64	Columbia Drive 591	0.09	446	94	0.39
L21	Laramie	ML6736B	0.00	0.28	CR 123-1/SOUTHWEST DR	0.18	207	70	0.28
L22	Laramie	ML9572B	0.00	1.14		0.15	108	31	1.14
L23	Laramie	ML6895B	0.00	1.00	Old Highway Burns West	0.49	261	52	1.00
L24	Laramie	ML6736B	0.00	0.28	123-1	0.18	207	70	0.28
L25	Laramie	ML9385B	10.84	11.50	154-1	0.09	213	78	0.66
L26	Laramie	ML6880B	4.95	8.39	210-2	0.23	199	74	3.44
L27	Laramie	ML6869B	100.01	100.36	Jefferson Road	0.17	302	81	0.35
L28	Laramie	ML6856B	0.00	2.50	Chalk Bluff/"78" Road	0.25	119	83	2.50
L29	Laramie	ML7017B	0.25	0.50	S. Avenue B-6	0.13	167	92	0.25
L30	Laramie	ML4019B	101.41	101.66		0.11	191	100	0.26

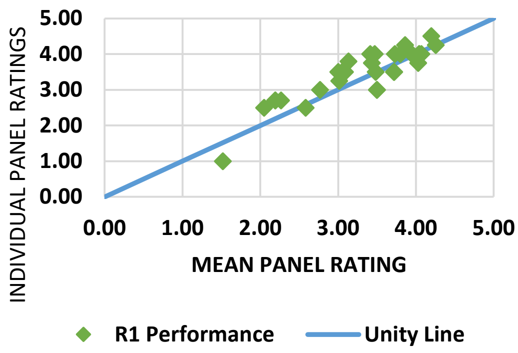
Appendix A-3: List of roadway segments that were used in the riding quality survey (Sedan vehicle)

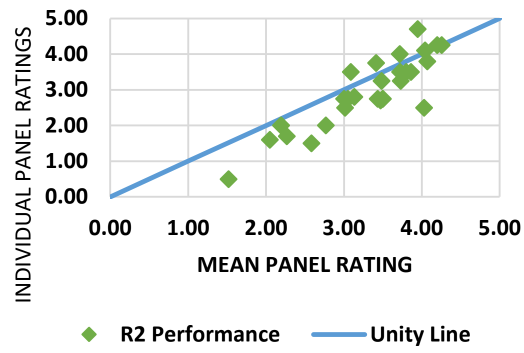
SN	COUNTY	Route	BegMP	EndMP	Primary Name	Rut	IRI	PCI	Length(miles)
L1	Laramie	ML6749B	0.400	1.110	129-1	0.07	128	89	0.71
L2	Laramie	ML7428B	0.000	0.470	HR Ranch Road	0.15	149	89	0.47
L3	Laramie	ML6868B	1.000	1.460	Allison Road U4056	0.18	161	100	0.46
L4	Laramie	ML6856B	2.750	3.160	Chalk Bluff/"78" Road	0.30	202	72	0.41
L5	Laramie	ML9382B	5.750	7.610	124-2	0.40	218	62	1.86
L6	Laramie	ML6895B	0.000	1.000	Old Highway Burns West	0.49	261	52	1.00
L7	Laramie	ML6856B	17.570	18.580	Chalk Bluff/"78" Road	0.12	59	100	1.01
L8	Laramie	ML6856B	23.980	24.240	Chalk Bluff/"78" Road	0.12	65	96	0.26
L9	Laramie	ML6875B	5.09	6.49	209-2	0.12	70	86	1.40
L10	Laramie	ML6774B	10.130	12.140	Hillsdale North Road/Midway	0.11	77	97	2.01
L11	Laramie	ML6749B	1.97	2.23	129-1	0.1	85	83	0.26
L12	Laramie	ML6875B	8.810	11.150	209-2	0.13	91	95	2.34
L13	Laramie	ML6744B	3.390	3.640	Avenue C U4019	0.09	114	90	0.25
L14	Laramie	ML6749B	0.400	1.110	129-1	0.07	128	89	0.71
L15	Laramie	ML6856B	3.160	7.250	Chalk Bluff/"78" Road	0.25	151	57	4.09
L16	Laramie	ML6743B	1.8	2.09	125-2	0.15	139	83	0.29
L17	Laramie	ML6921B	2.85	3.07	Ridley Road	0.13	172	85	0.22
L18	Laramie	ML6867B	0.100	0.650	Prosser Road	0.24	322	76	0.55
L19	Laramie	ML6895B	3.02	5.03	Old Highway Burns West	0.23	245	62	2.01
L20	Laramie	ML7102B	0	0.21		0.18	464	78	0.21
L21	Laramie	ML6736B	0	0.28	CR 123-1/SOUTHWEST DR	0.18	207	70	0.28
L22	Laramie	ML9572B	0	1.14		0.15	108	31	1.14
L23	Laramie	ML6719B	0	2.96		0.33	390	39	2.96
L25	Laramie	ML9385B	10.84	11.5	154-1	0.09	213	78	0.66
L26	Laramie	ML6880B	4.95	8.39	210-2	0.23	199	74	3.44
L27	Laramie	ML6869B	100.01	100.36	Jefferson Road	0.17	302	81	0.35
L28	Laramie	ML6856B	0	2.5	Chalk Bluff/"78" Road	0.25	119	83	2.50
L29	Laramie	ML7017B	0.25	0.5	S. Avenue B-6	0.13	167	92	0.25

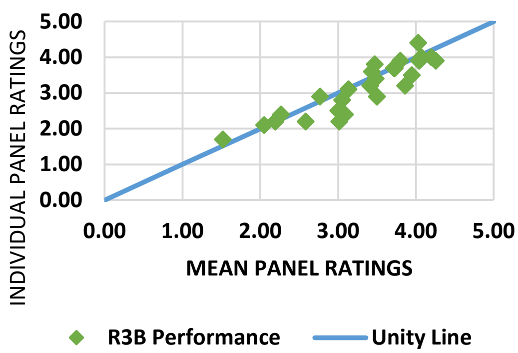
Appendix A-4: List of roadway sections that were used in the smartphones experiment

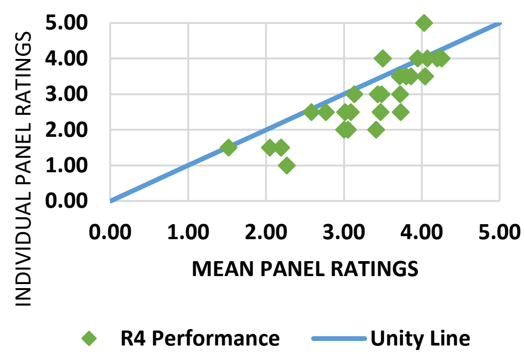
SN	Analysis	COUNTY	Route	BegMP	EndMP	Rut	IRI	PCI	Length
1	Modeling	Laramie	ML6856B	17.570	18.580	0.12	59	100	1.01
2		Albany	ML5060B	0.000	1.260	0.06	64	98	0.43
3		Laramie	ML6856B	22.630	23.400	0.12	66	100	0.63
4		Laramie	ML9382B	2.420	3.560	0.12	67	87	0.62
5		Laramie	ML6856B	23.400	23.620	0.12	69	100	0.77
6		Laramie	ML6774B	4.090	5.550	0.10	77	94	1.46
7		Laramie	ML6856B	24.87	25.64	0.15	90	89	0.34
8		Laramie	ML6763B	0	1.32	0.16	110	86	1.32
9		Laramie	ML6774B	16.3	17.21	0.19	113	70	0.05
10		Albany	ML5012B	0.5	2.54	0.11	118	85	0.41
11		Laramie	ML1102B	0.62	2.11	0.14	128	73	0.5
12		Albany	ML5012B	0.09	0.5	0.08	156	74	2.04
13		Laramie	ML6772B	1.04	2.05	0.18	166	70	1
14		Albany	ML5009B	0	0.22	0.09	169	89	0.2
15		Albany	ML5004B	0.5	0.83	0.17	181	84	0.33
16		Laramie	ML6895B	3.02	5.03	0.23	245	62	1
17		Laramie	ML6886B	1.4	1.54	0.11	270	85	1.4
18		Laramie	ML6867B	0.1	0.65	0.24	322	76	0.28
19		Laramie	ML6719B	0	2.96	0.33	390	39	0.53
20		Albany	ML5069B	0	0.5	0.31	359	64	0.5
21	Validation	Albany	ML5060B	1.260	2.680	0.07	57	100	1.26
22		Albany	ML5037B	0.300	0.600	0.13	59	100	0.28
23		Laramie	ML6875B	11.150	12.190	0.11	80	96	1.04
24		Laramie	ML6856B	25.64	26.19	0.17	98	91	0.02
25		Albany	ML5071B	0	5.57	0.12	109	82	1.43
26		Laramie	ML6745B	4.1	4.86	0.13	118	98	0.05
27		Laramie	ML6963B	0.23	2.05	0.24	122	81	0.18
28		Albany	ML5012B	2.59	3.89	0.11	124	87	0.05
29		Laramie	ML9540B	0	0.53	0.08	150	86	0.53
30		Laramie	ML6737B	4.65	6.8	0.2	168	82	2.15
31		Laramie	ML6856B	2.75	3.16	0.3	202	72	0.25
32		Laramie	ML9382B	5.75	7.61	0.4	218	62	0.46
33		Laramie	ML6895B	0	1	0.49	261	52	2.02
34		Laramie	ML6869B	100.01	100.36	0.17	302	81	0.15
35		Laramie	ML6719B	0.61	1.14	0.33	332	37	2.96

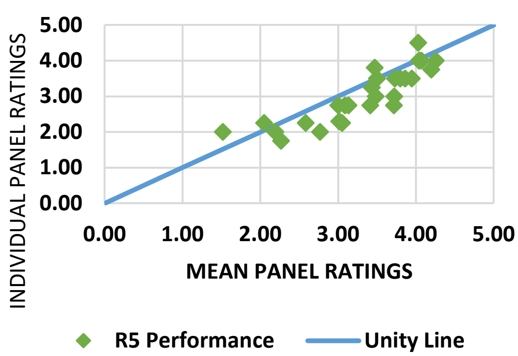
Appendix A-5: Individual panel ratings vs group (SUV)

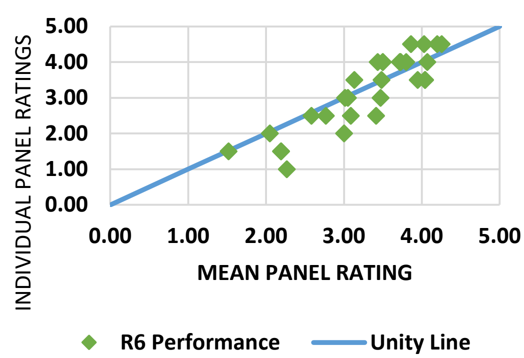


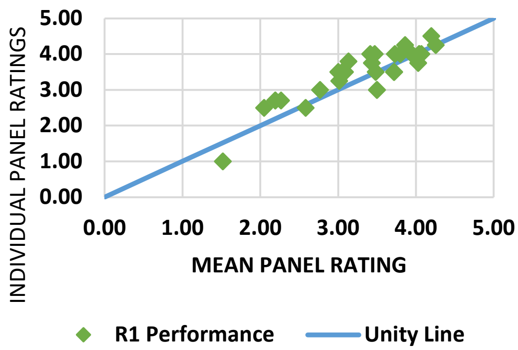








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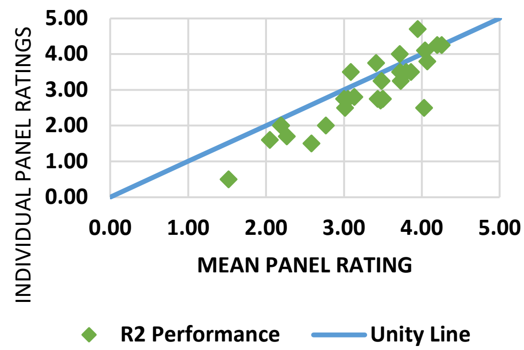
3.00
2.00
1.00
0.00
0.00 1.00 2.00 3.00 4.00 5.00
MEAN PANEL RATING
R1 Performance
Unity Line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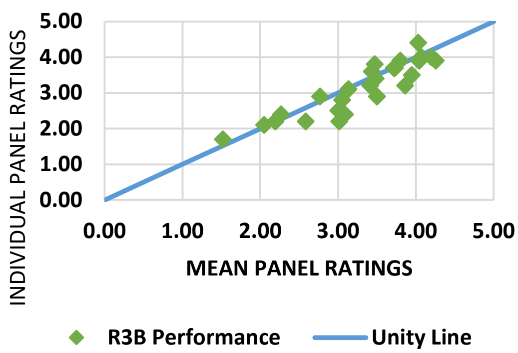
3.00
2.00
1.00
0.00
0.00 1.00 2.00 3.00 4.00 5.00
MEAN PANEL RATING
R2 Performance
Unity Line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1.00
0.00
0.00 1.00 2.00 3.00 4.00 5.00
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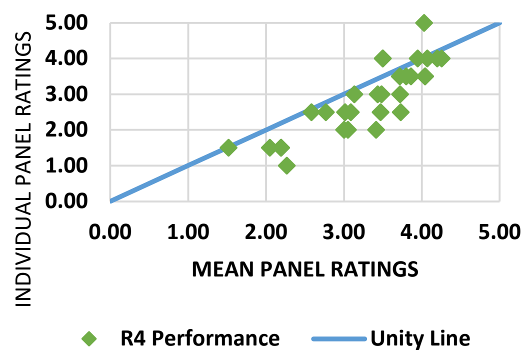
R3B Performance
Unity Line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R4 Performance
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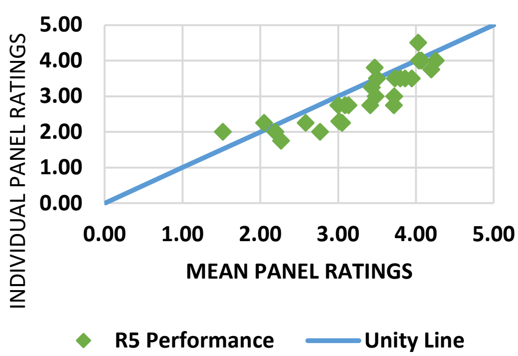
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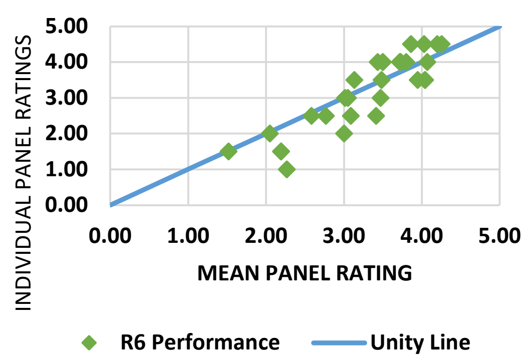
R5 Performance
Unity Line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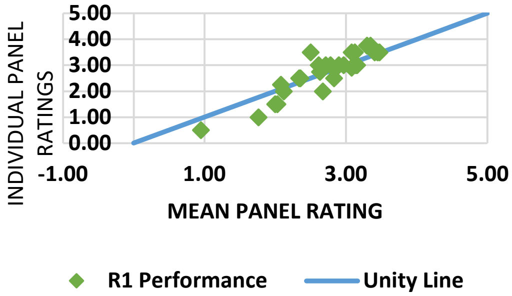
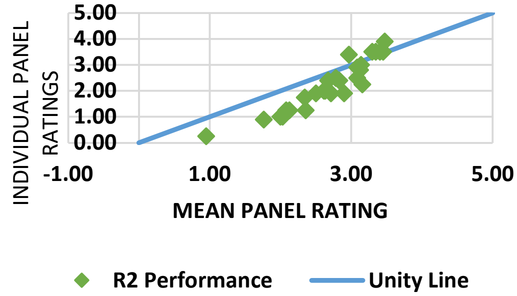
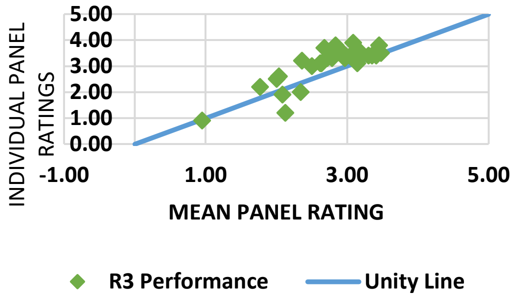
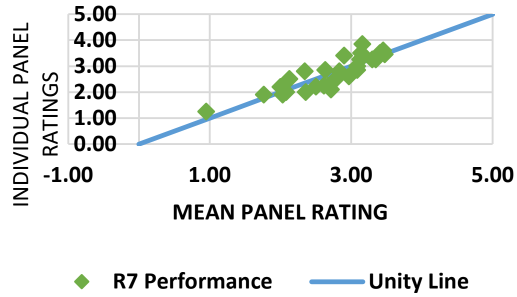
3.00
2.00
1.00
0.00
0.00 1.00 2.00 3.00 4.00 5.00
MEAN PANEL RATING
R6 Performance
Unity Line

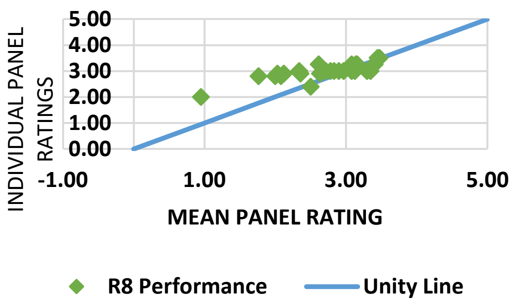
Appendix A-6: Individual panel ratings vs group (Sedan)

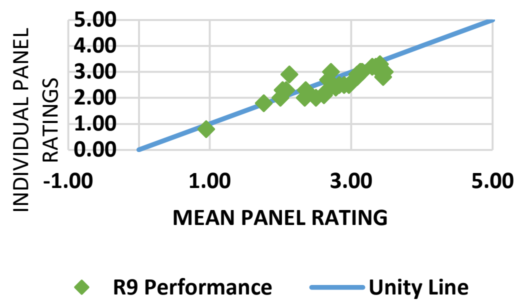


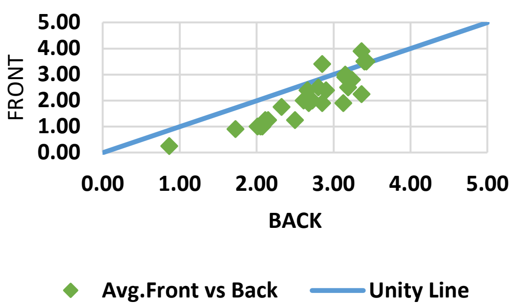












Appendix A-7: MATLAB Code for Cross-Correlation

```
>> %% %% Sampling rate
Fs=200;

%% Window Size
a=1;
b=[0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1];

%% Assigning and Loading Templates

%% for Template 1 where IRI < 70

a1 =  xlsread('Speed3 40.csv','C2:C19931');

%%  Median Filter with window = 5;
y1 = medfilt1(a1,5);

%%  Moving Average Filter with window = 10;
z1 = filter(b,a,y1);

%% for Template 2  where 70 < IRI< 100

a2 = xlsread('Speed38 40.csv','C2:C13033');

%%  Median Filter with window = 5;
y2 = medfilt1(a2,5);

%%  Moving Average Filter with window = 10;
z2 = filter(b,a,y2);

%% for Template 3  where 101< IRI< 130

a3 = xlsread('Speed8 40.csv','C2:C38333');

%%  Median Filter with window = 5;
y3 = medfilt1(a3,5);

%%  Moving Average Filter with window = 10;
z3 = filter(b,a,y3);

%% for Template 4 where 131< IRI< 170

a4 = xlsread('Speed12 40.csv','C2:C3501');
```

```
%% Plotting the results

figure
ax(1) = subplot(611);
plot(lag1/Fs,C1,'k');
ylabel('Amplitude');
grid on
title('Cross-correlation between Template 1 and Signal (IRI=77 in/mile)')
ax(2) = subplot(612);
plot(lag2/Fs,C2,'r');
ylabel('Amplitude');
grid on
title('Cross-correlation between Template 2 and Signal(IRI=77 in/mile)')
ax(3) = subplot(613);
plot(lag3/Fs,C3,'r');
ylabel('Amplitude');
grid on
title('Cross-correlation between Template 3 and Signal(IRI=77 in/mile)')
ax(4) = subplot(614);
plot(lag4/Fs,C4,'r');
ylabel('Amplitude');
grid on
title('Cross-correlation between Template 4 and Signal(IRI=77 in/mile)')
ax(5) = subplot(615);
plot(lag5/Fs,C5,'r');
ylabel('Amplitude');
grid on
title('Cross-correlation between Template 5 and Signal(IRI=77 in/mile)')

%% Finding the points of highes amplitude to identify Signals Similarities

m1=max(C1)
m2=max(C2)
m3=max(C3)
m4=max(C4)
m5=max(C5)
```

```
%%  Median Filter with window = 5;
y4 = medfilt1(a4,5);

%%  Moving Average Filter with window = 10;
z4 = filter(b,a,y4);

%% for Template 5  where IRI>170
a5 = xlsread('Speed24 40.csv','C2:C37940');

%%  Median Filter with window = 5;
y5 = medfilt1(a5,5);

%%  Moving Average Filter with window = 10;
z5 = filter(b,a,y5);



%% for Signal

s = xlsread('Speed49 40.csv','C2:C25694');

%%  Median Filter with window = 5;
y = medfilt1(s,5);

%%  Moving Average Filter with window = 10;
z = filter(b,a,y);

%% Finding Signal Similarities

[C1,lag1] = xcorr(z1,z);
[C2,lag2] = xcorr(z2,z);
[C3,lag3] = xcorr(z3,z);
[C4,lag4] = xcorr(z4,z);
[C5,lag5] = xcorr(z5,z);
```

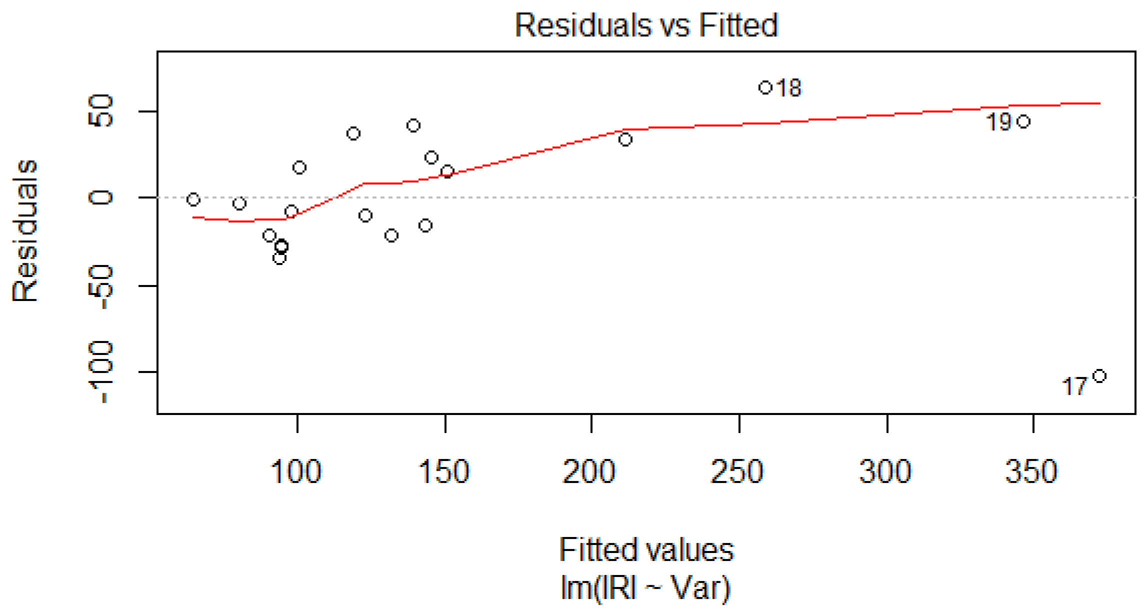
Appendix A-8: MATLAB Code for Welch periodogram estimates

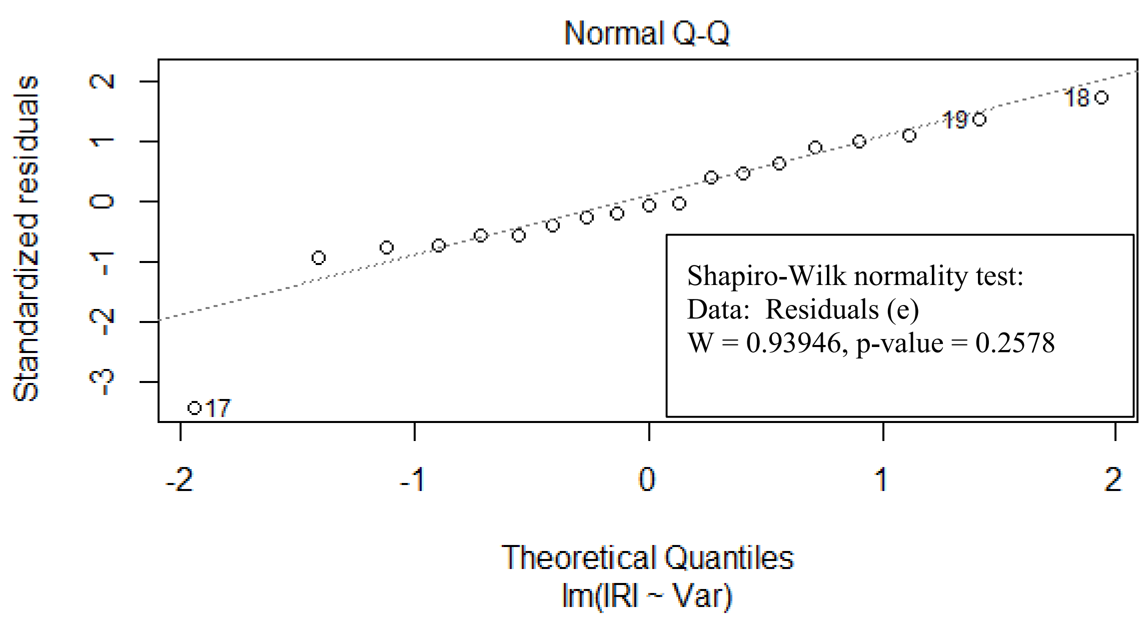
```
>> %% Sampling rate
Fs=200;
%% Window Size ,segments, smoothing window, and overlap for moving average filter
a=1;
b=[0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1 0.1];

segmentLength1 = 500;
noverlap1 = 300;

%% Assigning and Loading Templates

%% for Template 1 where IRI < 70
a1 =  xlsread('Speed3 40.csv','C2:C19931');

%%  Median Filter with window = 5;
y1 = medfilt1(a1,5);

%%  Moving Average Filter with window = 10;
z1 = filter(b,a,y1);

[pxx1,f1] = pwelch(z1,segmentLength1,noverlap1,500,Fs);

%% for Template 2 where 70 < IRI< 100
a2 = xlsread('Speed38 40.csv','C2:C13033');

%%  Median Filter with window = 5;
y2 = medfilt1(a2,5);

%%  Moving Average Filter with window = 10;
z2 = filter(b,a,y2);

[pxx2,f2]= pwelch(z2,segmentLength1,noverlap1,500,Fs);


%% for Template 3 where 101< IRI< 130

a3 = xlsread('Speed8 40.csv','C2:C38333');

%%  Median Filter with window = 5;
y3 = medfilt1(a3,5);

%%  Moving Average Filter with window = 10;
z3 = filter(b,a,y3);
```

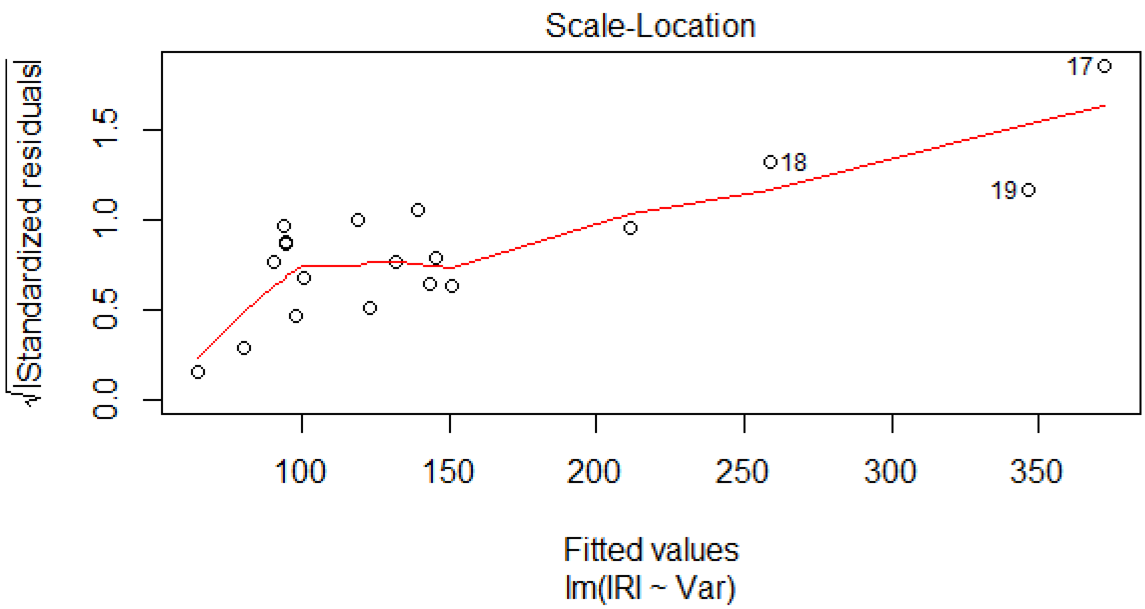
```
[pxx3,f3]= pwelch(z3,segmentLength1,noverlap1,500,Fs);

%% for Template 4 where 131< IRI< 170

a4 = xlsread('Speed12 40.csv','C2:C3501');
%%  Median Filter with window = 5;
y4 = medfilt1(a4,5);

%%  Moving Average Filter with window = 10;
z4 = filter(b,a,y4);

[pxx4,f4] = pwelch(z4,segmentLength1,noverlap1,500,Fs);


%% for Template 5 where IRI>170
a5 = xlsread('Speed24 40.csv','C2:C37940');

%%  Median Filter with window = 5;
y5 = medfilt1(a5,5);

%%  Moving Average Filter with window = 10;
z5 = filter(b,a,y5);

[pxx5,f5] = pwelch(z5,segmentLength1,noverlap1,500,Fs);

%% Plotting the results

figure
ax(1) = subplot(611);
plot(f1,10*log10(pxx1),'k');
ylabel('Magnitude (dB)');
grid on
title('IRI= 64 in/mile')

ax(2) = subplot(612);
plot(f2,10*log10(pxx2),'k');
ylabel('Magnitude (dB)');
grid on
title('IRI= 90 in/mile')
```

```
ax(3) = subplot(613);
plot(f3,10*log10(pxx3),'k');
ylabel('Magnitude (dB)');
grid on
title('IRI= 118 in/mile')

ax(4) = subplot(614);
plot(f4,10*log10(pxx4),'k');
ylabel('Magnitude (dB)');
grid on
title('IRI= 169 in/mile')

ax(5) = subplot(615);
plot(f5,10*log10(pxx5),'k');
xlabel('Frequency (Hz)')
ylabel('Magnitude (dB)');
grid on
title('IRI= 245 in/mile')
```

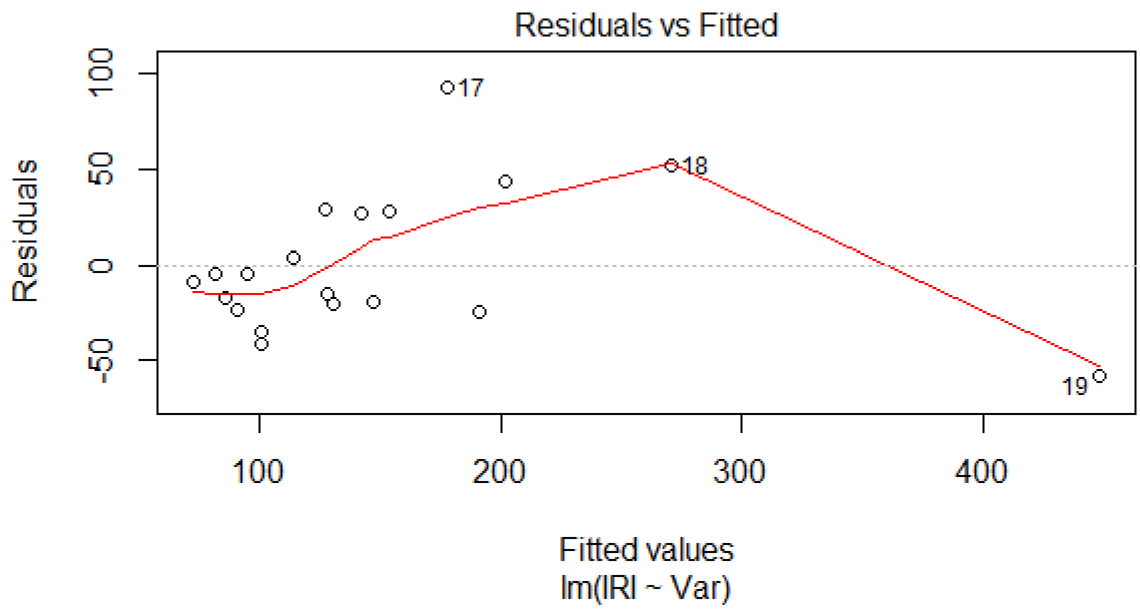
Appendix A-9: Diagnostic Plots for variance model at 40mph (Equation 14)

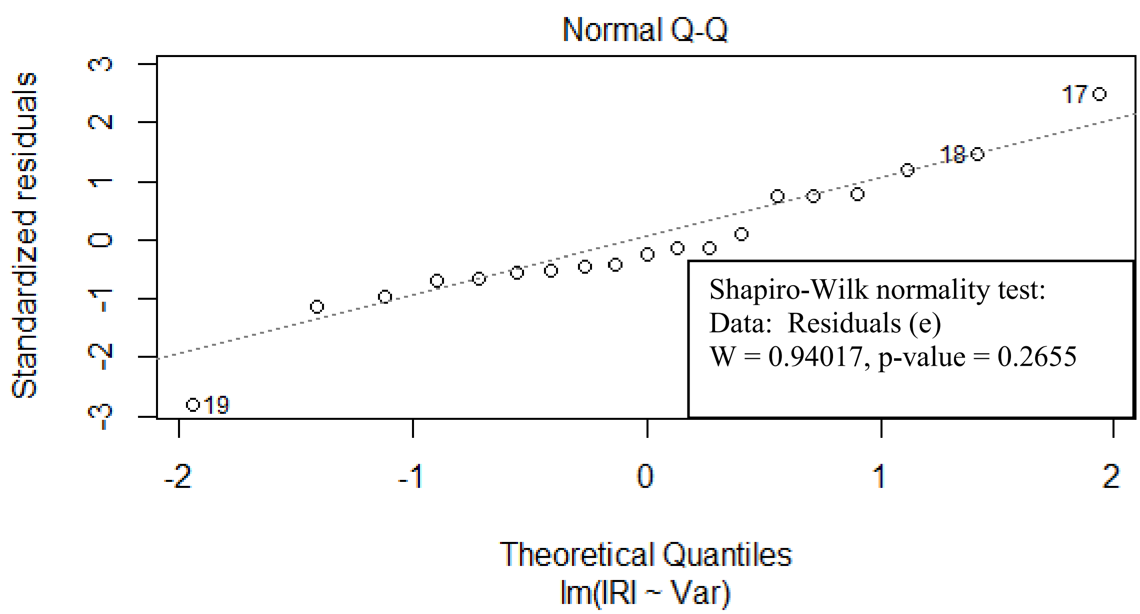


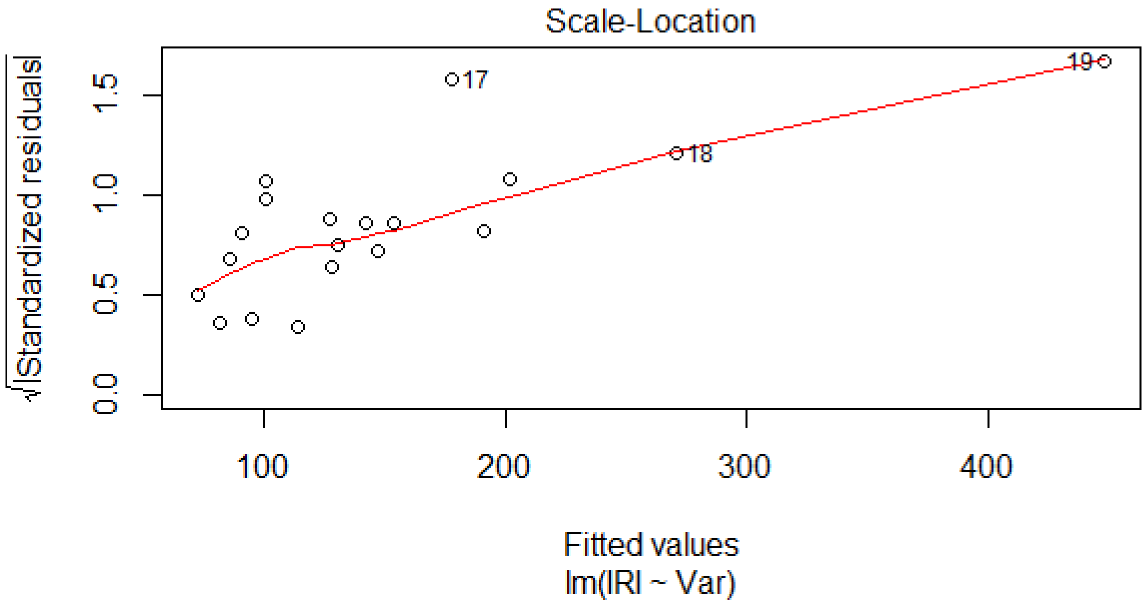



Scale-Location
√|Standardized residuals|
0.0
0.5
1.0
1.5
100
150
200
250
300
350
17
18
19
Fitted values
lm(IRI ~ Var)

Appendix A-10: Diagnostic Plots for variance model at 50mph (Equation 15)






Scale-Location
√|Standardized residuals|
0.0
0.5
1.0
1.5
100
200
300
400
17
18
19
Fitted values
lm(IRI ~ Var)