A NETWORK-LEVEL DECISION MAKING TOOL FOR PAVEMENT MAINTENANCE AND USER SAFETY

FINAL PROJECT REPORT

by

Sogol Haddadi, Erdem Coleri, and Blaine Wruck

101 Kearney Hall
Oregon State University
Corvallis, OR, 97331

for

Pacific Northwest Transportation Consortium (PacTrans)
USDOT University Transportation Center for Federal Region 10
University of Washington
More Hall 112, Box 352700
Seattle, WA 98195-2700

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16. Abstract

Although inflation has raised the cost of paving, pavement program funding levels are about 30 percent lower than a decade ago. Resurfacing treatments typically last 10 to 20 years, but current pavement funding only allows for resurfacing every 30 years or longer. Therefore, higher user costs (mostly related to vehicle maintenance and fuel consumption) are expected to be observed as a result of increased pavement roughness. The goal of this study was to develop a network-level decision-making tool (software) to suggest the most efficient maintenance and rehabilitation strategies by minimizing user and agency costs and maximizing their benefits. This study also investigated the use of a maximum roughness level of 5 m/km to increase user safety. The project also evaluated the effects of different trigger roughness levels (trigger IRIs) and different treatment methods (1. use of one value for trigger International Roughness Index (IRI) for all sections regardless of traffic levels, and 2. use of different trigger IRIs for sections on the basis of their traffic levels) on user benefits and agency costs. This study found the first method to be more optimal. In addition, results showed that optimal trigger IRI depends on the available budget level. Use of a lower value for trigger IRI requires a higher budget level and increases user benefits.

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List of Abbreviations

AADT:	Average Annual Daily Traffic
AADTT:	Average Annual Daily Truck Traffic
AC:	Asphalt Concrete
B/C:	Benefit-to-Cost Ratios
CRCP:	Continuously Reinforced Concrete Pavement
DGAC:	Dense Graded Asphalt Concrete
DGAC-CS:	Chip Seal on Dense Graded Asphalt Concrete
DGAC-CSMB:	Chip Seal with Modified Binder on Dense Graded Asphalt Concrete
DGAC-SS:	Slurry Seal on Dense Graded Asphalt Concrete
DI:	Distress Index
DOT:	Department of Transportation
ESAL:	Equivalent Single Axle Loads
FHWA:	Federal Highway Administration
GHG:	Greenhouse Gas
GIS:	Geographic Information Systems
GWP:	Global Warming Potential
HDM:	Highway Development and Management Model
HMA:	Hot Mix Asphalt Concrete
IRI:	International Roughness Index
LCA:	Life Cycle Analysis
LCCA:	Life Cycle Cost Analysis
LCI:	Life Cycle Inventory Assessment
LCO:	Life Cycle Optimization
LTPP:	Long Term Pavement Performance
MATLAB:	Matrix Laboratory Software
MDOT:	Michigan Department of Transportation
MEPDG:	Mechanistic-Empirical Pavement Design Guide
MPD:	Mean Profile Depth
NCDOT:	North Carolina Department of Transportation
NPV:	Net Present Value
ODOT:	Oregon Department of Transportation
OGAC:	Open Graded Asphalt Concrete
PacTrans:	Pacific Northwest Transportation Consortium
PCC:	Portland Cement Concrete
PSI:	Pavement Serviceability Index
PSR:	Present Serviceability Rating
RAP:	Reclaimed Asphalt Pavement
RAPHL:	Hot-Laid Reclaimed Asphalt Pavement
SUV:	Sport Utility Vehicle
TRIP:	National Transportation Research Group
VOC:	Vehicle Operating Costs
VMT:	Vehicle Miles Travelled

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Executive Summary

General Background and Problem Statement

The 2012 Pavement Condition Report released by the Oregon Department of Transportation (ODOT) (ODOT, 2013) indicated that pavement program funding levels are about 30 percent less than they were a decade ago while inflation has simultaneously raised the cost of paving. Resurfacing treatments typically last 10 to 20 years, but current pavement funding only allows for resurfacing every 30 years or more. Therefore, higher user costs (mostly related to vehicle maintenance and fuel consumption) are expected as a result of increased pavement roughness. Although performance-based pavement design procedures have been implemented by all state departments of transportation (DOTs), pavement roughness and vehicle operating costs are not directly considered in the decision making process. Recent research (Chatti and Zaabar, 2012; EAPA, 2004) has shown that consideration of vehicle maintenance and fuel consumption costs in pavement design can change current maintenance and rehabilitation strategies. International Roughness Index (IRI) trigger values for different climate regions and traffic levels in the Pacific Northwest need to be determined by considering agency-user costs and road user safety.

Key Methodology

In this study, a prototype, network-level decision-making tool was developed to select the most efficient pavement maintenance and rehabilitation strategies to minimize costs and maximize benefits for agencies and users. Field data from 91 roadway sections in Oregon, Idaho, Washington, and California were used to develop and test the tool. Field data associated with maintenance history, location, pavement structure, profile, and traffic were obtained from the Federal Highway Administration (FHWA) website LTPP InfoPave (2016) for all the sections.

The data set included previous treatment types, previous treatment thicknesses, annual average daily traffic (AADT), annual average daily truck traffic (AADTT) and annually collected IRI data for each of the last treatments.

In this study, pavement conditions were evaluated over a 40-year analysis period. Traffic data in terms of AADTT and AADT for the past years were used to develop linear models to predict the traffic for each section over the analysis period. With annually collected IRI data for the past years and treatments, nonlinear models were developed to predict the pavement performance in terms of IRI for each section. To find the optimal budget allocation for pavement maintenance and rehabilitation, a code was developed by using MATLAB 2016. Data corresponding to traffic, treatment types and thicknesses, annual IRI, and material and construction costs were used as inputs to the developed software. For each section, IRI and the net present value (NPV) of user benefits were estimated for each year. If the estimated IRI reached the trigger IRI, then a treatment was applied and the NPV of agency cost was estimated. If the predicted IRI was less than the trigger IRI, then a "do nothing" scenario was chosen, and the IRI for the next year was predicted for the existing treatment type. This procedure was continued until the 40-year analysis period was reached. With agency costs and user benefits based on the treatment types and the frequency of resurfacing for each section, sections were ranked according to benefit-to-cost (B/C) ratios over the analysis period. Subsequently, the available budget was allocated to the sections with highest priority for treatment (sections with highest B/C ratios). This process was continued until the budget was expended.

To extend the utility of the network-level decision-making tool developed in this study, a prototype GIS map was created with ArcGIS in order to investigate the feasibility of integrating the results of the decision-making tool with the spatial referencing power of GIS. The goal of the GIS map was to create the ability for users to import LTPP road section data and the tool's MATLAB results into the GIS environment; spatially catalog this information; and then rank, highlight, and export selected roadway sections that present the highest benefit-to-cost ratios, or highest maintenance priority, to a shareable data layer. To prove the methodology of the GIS process, 20 sections (5 sections in Oregon and 15 sections in Idaho) in the LTPP database were selected to spatially catalog. MATLAB outputs for single trigger IRI of 170 inches/mile were arbitrarily selected as trial subjects. Then, sections with the highest priority to receive maintenance and rehabilitation for a given budget and trigger IRI value were located geographically. Spatial visualization of the decision-making tool results will help stakeholders to pinpoint where particular sections are and which sections should be maintained.

Major Findings and Their Implications

The results of this study showed that as the budget increases, the trigger IRI at which the user benefit is maximum decreases. The authors also conclude that the method of considering one value for trigger IRI regardless of traffic levels is more optimal for maximizing benefits than the Madanat (2014) method. The study also determined that budget level controls the most optimal trigger IRI. By allocating a higher budget level to road maintenance (considering a lower value for trigger IRI), higher user benefits can be obtained.

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Chapter 1 Introduction

The 2012 Pavement Condition Report released by the Oregon Department of Transportation (ODOT) (2013) indicated that pavement program funding levels are about 30 percent less than they were a decade ago, while inflation has simultaneously raised the cost of paving. Resurfacing treatments typically last 10 to 20 years, but current pavement rehabilitation funding allows for resurfacing only every 30 years at a minimum. Therefore, higher user costs (mostly related to vehicle maintenance and fuel consumption) are expected to be observed as a result of increased pavement roughness. Although performance-based pavement design procedures have been implemented by all state departments of transportation (DOTs), pavement roughness and vehicle operating costs are not directly considered in the decision-making process. Recent research by Chatti and Zaabar (2012) and the European Asphalt Pavement Association (EAPA) (2004) has shown that consideration of vehicle maintenance and fuel consumption costs in pavement design can change current maintenance and rehabilitation strategies. The International Roughness Index (IRI) is used for quantifying the longitudinal profile of the traveled wheel track, and it is computed as the cumulative suspension displacement per unit of distance traveled and expressed as m/km or inches/mile. Trigger IRI is a value for IRI indicating failure of the pavement. Trigger IRI values for different climate regions and traffic levels in the Pacific Northwest need to be determined by considering agency-user costs and safety. When the IRI reaches the trigger point, maintenance and rehabilitation are required.

A National Transportation Research Group (TRIP) (2015) reported that more than 28 percent of urban roads, including interstates, freeways, and arterial routes, are in substandard condition with IRIs above 170 inches/mile (2.68 m/km), providing poor ride quality and increased fuel/maintenance costs for road users. TRIP (2015) reported that 41 percent of urban roads are in mediocre and fair condition with IRIs of between 95 and 170 inches/mile and acceptable driving quality, and 31 percent are in good condition with IRI ratings of below 95 inches/mile. TRIP (2015) also posited that road users in urban areas with populations exceeding 500,000 pay an additional $516 annually by driving on poor condition pavements because of increased fuel consumption, vehicle maintenance/repair costs, and accelerated vehicle deterioration. Substandard road conditions cost drivers on a national level about $109.3 billion annually in terms of vehicle operating costs (VOC).

The impact of road roughness and surface texture on user safety is also an important issue in the decision-making process. Although reducing road roughness and surface texture decreases road user costs, it can also reduce skid resistance, which can increase accident rates, especially during rain events. On the other hand, although skid resistance increases over time as a result of increased roughness and road texture, accumulation of severe cracks, rutting, and potholes on roads can also create safety issues. For these reasons, the impacts of pavement distresses and changes in roughness and texture (during the use phase and after construction) on road user safety should be considered in the pavement maintenance and rehabilitation decision-making process. Upper and lower limits on roughness, texture and distress (trigger values) should be set to ensure user safety. This study used a maximum IRI of 5 m/km for pavement maintenance and rehabilitation to increase safety and to reduce accident rates (Tighe et al. 2000).

1.1 Key Objectives of This Study

The objectives of this study were as follows:

- Develop a network-level decision-making tool to select the most efficient pavement maintenance and rehabilitation strategies to minimize agency and user costs and maximize their benefits.

- Find the optimal trigger IRI for different budget levels to maximize user benefits by considering user safety.
- Compare different treatment methods, namely 1) using one value for trigger IRI for all sections regardless of the traffic levels, and 2) using different trigger IRIs for sections on the basis of their traffic levels.
- Integrate the developed decision-making tool with geographic information systems (GIS).

1.2 Organization of the Report

This introduction section is followed by the literature review in Chapter 2. The research methodology and procedures for developing the decision-making tool are discussed in Chapter 3. Chapter 4 describes the results of simulations conducted with the developed decision-making tool. In addition, a comparison of the different treatment methods described above (1. use one value for trigger IRI for all the sections regardless of the traffic levels, and 2. use different trigger IRIs for sections on the basis of their traffic levels) is described, and optimal trigger IRIs for different budget levels are suggested. Chapter 5 summarizes the process followed to integrate the developed decision-making tool with GIS. Conclusions, future recommendations, and suggested implementation strategies are presented in Chapter 6.

Chapter 2 Literature Review

2.1 Pavement Roughness

Roughness refers to the irregularity of the pavement surface resulting in poor ride quality for road users. Roughness can be measured by the Present Serviceability Rating (PSR). PSR is the mean roughness on a 0 to 5 scale given by a panel of passengers in a vehicle (Al-Omari and Darter 1994). PSR is a subjective/judgmental observation about the serviceability of the pavement, and it reflects the ride quality based on passenger interpretations. Therefore, it can be considered to be a measurement of roughness, since roughness and ride quality are correlated (Pavement Interactive 2017). Figure 2.1 shows the chart used for rating pavement serviceability. Roughness can be also measured by the International Roughness Index (IRI). IRI is the most common index used for quantifying road roughness (Pavement Interactive 2017). IRI is computed as the cumulative vertical suspension displacement per unit of distance traveled and is expressed as m/km or inches/mile. It is used for quantifying the longitudinal roughness of the traveled wheel track. Figure 2.2 represents the IRI scale for different pavement types and conditions (Pavement Interactive 2017). To measure IRI, vehicles equipped with inertial profilers are driven at highway speeds to measure surface profiles. The quarter-car model, a mathematical model representing a single wheel moving on a pavement texture, is used to convert the surface profile to vertical vehicle suspension movement and roughness (Sayers 1986).

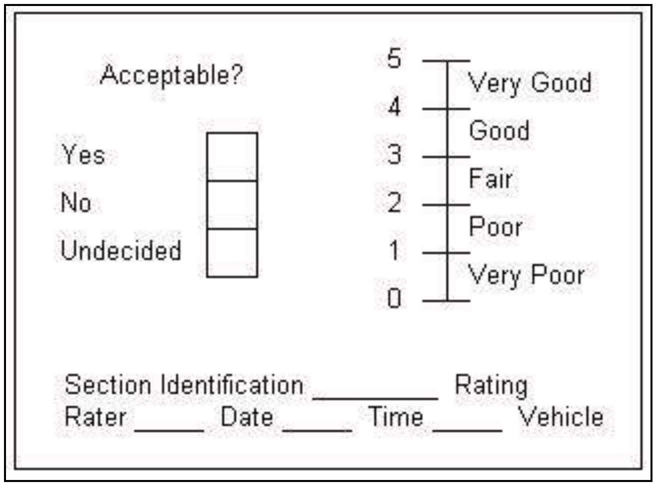

Figure 2.1. PSR rating (Pavement Interactive 2017)

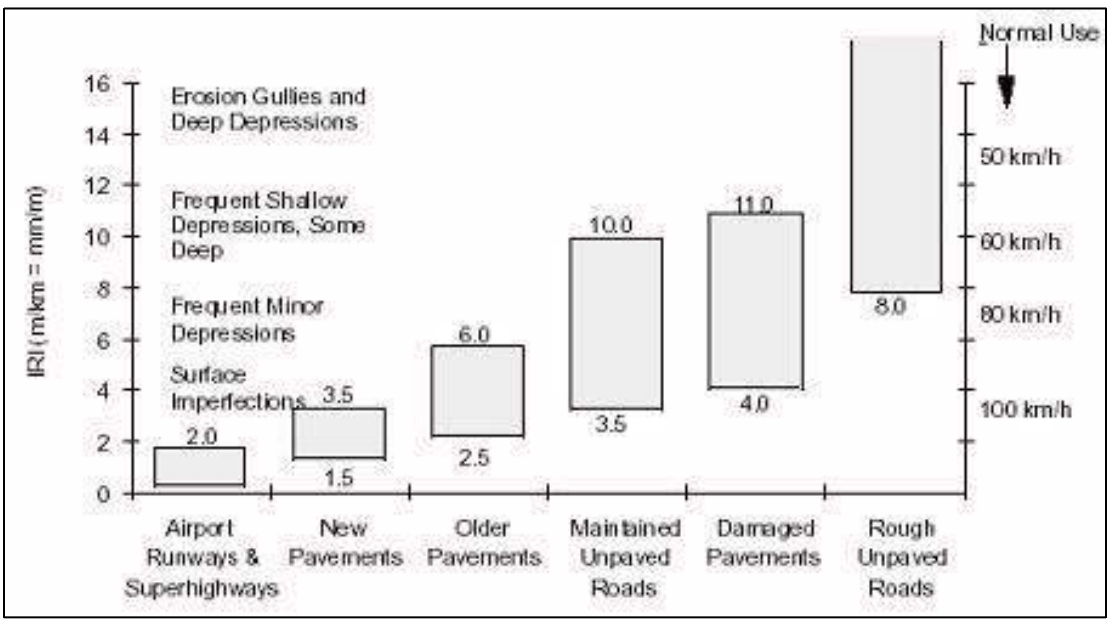

Figure 2.2. IRI roughness scale (Pavement Interactive 2017)

2.2 Effects of Roughness on Vehicle Operating Costs

Costs related to operating a vehicle, such as fuel consumption, oil and lubrication, tire wear, repair and maintenance, depreciation, license, and insurance, are referred to as vehicle operating costs (VOC). VOC models attempt to model fuel and oil consumption, repair and maintenance, depreciation, and tire wear separately and to estimate total vehicle operating costs by summing them all together (Chatti and Zaabar 2012). Since the IRI directly affects VOCs and ride quality (user comfort), it is used to describe the condition of the roadways (Sayers et al. 1986).

The Highway Development and Management model (HDM) was developed by the World Bank in 1977. It is a computer model used for cost estimation of construction, maintenance, and roadway use. Since roadway user cost is a major part of transportation costs, it is the most important part to be precisely evaluated. In the HDM-4 model, fuel consumption, oil and lubricant consumption, labor hours, parts usage, depreciation, interest, and overhead are included in the total VOCs. These costs can be affected by pavement condition, roadway geometry, operating speed, and other factors related to vehicle type and technology (Bennett and Greenwood 2003). Although HDM-4 is expected to be an effective tool for VOC calculations, HDM-4 models were originally developed on the basis of data from developing countries and needed to be calibrated with data from the U.S.

Chatti and Zabaar (2012) calibrated HDM-4 models by considering United States vehicle types, load levels, and pavement conditions. Fuel consumption, tire wear, and repair and maintenance costs, which are the factors most heavily affected by pavement conditions, were measured and evaluated. To accomplish this objective, surveys were conducted to collect data on pavement condition, and field tests were performed to collect fuel consumption and tire wear data. Then, the collected data were used to validate and calibrate the HDM-4 fuel consumption and tire wear models. Additionally, mechanistic-empirical repair and maintenance models were developed for a full range of vehicle types and were designed to be compatible with the pavement conditions of the United States. Results showed that for the speed of 55 mph (88 km/h) at 30^{o}C with a mean profile depth (MPD) of 1 mm and a surface grade of 0 percent, increasing the IRI from 63.4 inches/mile to 190.2 inches/mile (1 m/km to 3 m/km) increased fuel consumption by around 1.8 percent for light trucks and by 2.9 percent for articulated trucks. An IRI increase of 63.4 inches/mile (1 m/km) resulted in a fuel consumption increase of around 2 percent for passenger cars regardless of their speed. This study also found that, for a 17^{o}C temperature, a 1-mm (0.04-inches) MPD, and a 0 percent grade, a 63.4 inches/mile (1 m/km) reduction in IRI reduced tire wear costs by around 1 percent. This reduction had a tendency to increase with vehicle speeds for passenger cars. Moreover, the authors concluded that there was no significant effect of IRI on vehicle maintenance and repair costs when IRI values were lower than 190.08 inches/mile (3 m/km). After this threshold, an increase in IRI of about 1 m/km increased the repair and maintenance costs around 10 percent for passenger cars and heavy trucks. Increases in IRI of up to 316.8 inches/mile (5 m/km) resulted in maintenance cost increases of 40 percent for passenger cars and 50 percent for heavy trucks.

The WesTrack research study (Mitchell 2000) was conducted in Nevada to estimate the effects of pavement smoothness on the fuel and maintenance costs of trucks. Four trucks applied about 4.9 million 80-kN equivalent single axle loads[1] (ESALs) in this project before and after rehabilitation of a specific pavement section. The section was milled around 100 mm and resurfaced to improve the IRI of the pavement by at least 10 percent. The average fuel consumption of four trucks over the eight-week period prior to rehabilitation was estimated to be 4.2mi/gal (1.79 km/l) and about 4.4 mi/gal (10.35 km/l) over the seven-week period after rehabilitation. The improvement in fuel economy due to the reduction of IRI was about 4.5

[1]ESAL is a concept to compare the pavement damage caused by wheel loads with different magnitudes and repetitions. For this reason, different axle types with various carried loads are converted to a reference axle load. The reference axle load is an 18000-lb single-axle with dual tires (Pavement Interactive 2017).

percent. Moreover, as the roughness of the pavement increased, the frequency of the failure of truck components increased as well. The four trucks' trailers tested in this study had a total of 40 springs. Eight trailer springs failed eight weeks before the resurfacing during the application of 265,000 ESALs. However, only one trailer spring failed in the seven-week period after rehabilitation during the application of 350,000 ESALs. Figure 2.3 shows the number of spring failures per million ESALs.

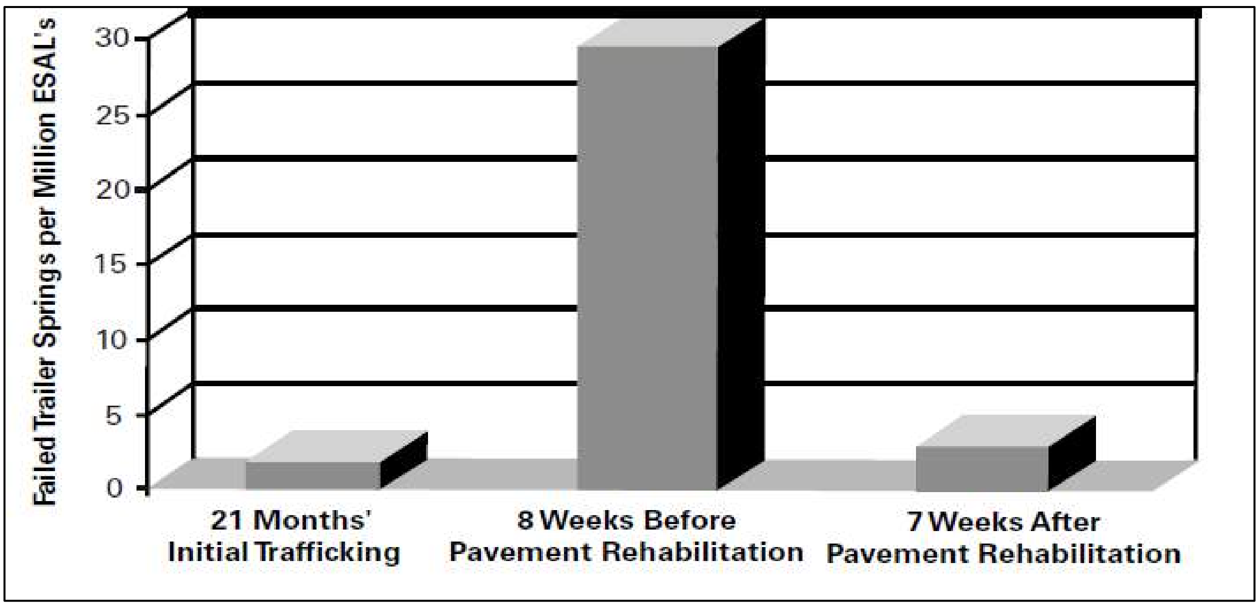

Figure 2.3. Effects of pavement condition on truck health (Mitchell 2000)

Barnes and Langworthy (2004) estimated the per-mile costs of operating automobiles and trucks by applying adjustment factors on costs derived from previous studies. Fuel consumption, maintenance and repair, tire replacement, and depreciation were estimated as marginal VOCs. A smooth pavement condition (PSI=3.5, IRI=80 inches/mile) was considered to be the baseline pavement condition. Marginal VOCs were measured for automobiles, pickups (including other large personal vehicles such as vans and SUVs), and commercial trucks. Results showed that fuel consumption was the primary cost component, followed by maintenance/repair costs and tire wear/replacement costs. Comparing the baseline condition with a city driving condition (frequent stops and starts), total marginal costs increased by about 3.8 cents per mile for automobiles and about 9.5 cents per mile for trucks. Rough pavements (PSI=2, IRI=170 inches/mile) increased the total marginal baseline costs by about 2.7 cents per mile for personal vehicles and 5.5 cents per mile for trucks. Barnes and Langworthy (2004) did not include the effects of roughness on fuel consumption. Detailed representations of the influence of pavement roughness and city driving conditions on VOCs are shown in table 2.1 to table 2.3. The study reported that city driving conditions, with frequent stops and starts, could increase fuel consumption from 5.0 to 7.0 cents per mile for automobiles, 7.8 to 10.1 cents per mile for pickups/vans/SUVs, and 21.4 to 28.0 cents per mile for commercial trucks. Since the effects of roughness on fuel consumption were not considered, rough roadways with poor ride quality did not increase fuel consumption in the Barnes and Langworthy (2004) report (table 2.3). Rough pavements with PSI=2 increased maintenance and repair costs around 0.8, cents per mile for automobiles, 0.9 cents/mile for pickups/vans/SUVs, and 2.6 centers/mile for commercial trucks. Likewise, tire wear/replacement costs on extremely rough pavements were estimated to be 17.9, cents per mile for automobiles, 22.0 cents/mile for pickups/vans/SUVs, and 48.9 cents/mile for commercial trucks.

Table 2.1. Baseline costs (cents per mile) (Barnes and Langworthy 2004)

Cost Category	Automobiles	Pickup/Van/SUV	Commercial Trucks
Total Marginal Costs	15.3	19.2	43.4
Fuel	5.1	7.8	21.4
Maintenance/Repair	3.1	3.7	10.5
Tires	0.9	1.0	3.5
Depreciation	6.2	6.7	0.8

Table 2.2. Costs with city driving conditions (cents per mile) (Barnes and Langworthy 2004)

Cost Category	Automobiles	Pickup/Van/SUV	Commercial Trucks
Total Marginal Costs	19.1	23.1	52.9
Fuel	7.0	10.1	28.0
Maintenance/Repair	3.7	4.2	12.1
Tires	0.9	1.0	3.5
Depreciation	7.5	7.7	9.2

Table 2.3. Costs for poor pavement quality (cents per mile) (Barnes and Langworthy 2004)

Cost Category	Automobiles	Pickup/Van/SUV	Commercial Trucks
Total Marginal Costs	17.9	22.0	48.9
Fuel	5.1	7.8	21.4
Maintenance/Repair	3.9	4.6	13.1
Tires	1.1	1.2	4.4
Depreciation	7.8	8.4	10.0

Islam and Buttlar (2012) derived equations to relate the IRI factor to fuel consumption, tire-wear costs, rehabilitation and maintenance costs, and depreciation costs on the basis of results from previous studies. Their study also estimated the impacts of different maintenance and rehabilitation scenarios on VOCs. They used the Mechanical-Empirical Pavement Design Guide (MEPDG) for predicting the roughness of the pavement in terms of IRI at different traffic levels, initial IRIs, and weather conditions. Increases in VOCs with increasing IRI are illustrated in table 2.4. The authors also suggested new maintenance and rehabilitation strategies, such as resurfacing every seven years instead of every 10 years, and concluded that it would be possible to save $5.1 million to $5.7 million (37 percent to 52 percent) in user costs over a 35-year life-cycle period with an additional $108,000 investment from agencies.

Table 2.4. Increases in user costs for passenger cars and pickup trucks due to pavement roughness (Islam and Buttlar 2012)

IRI (in./mi)	Increase in Fuel Cost ($/mi)	Increase in R&M costs ($/mi)	Increase in depreciation costs ($/mi)	Increase in tire costs ($/mi)	Total increase in user costs ($/mi)	Total cost per year for 10,000 vehicles ($)	Total costs per year per vehicle ($)
63.00	0.00000	0	0	0	0.00000	----------	----------
76.3	0.00031	0	0.00008	0	0.00039	46,428	5
80.1	0.00040	0	0.00024	0	0.00063	75,841	8
83	0.00046	0	0.00035	0	0.00082	98,113	10
86.6	0.00055	0.000742	0.00050	0	0.00179	214,581	21
89.6	0.00062	0.001575	0.00061	0.00016	0.00297	356,126	36
93.5	0.00071	0.002648	0.00077	0.00036	0.00449	538,386	54
98.5	0.00083	0.004009	0.00096	0.00061	0.00641	769,284	77
101.4	0.00090	0.00479	0.00106	0.00076	0.00751	901,780	90
104.3	0.00097	0.005565	0.00117	0.00090	0.00861	1,033,230	103
1083	0.00106	0.006625	0.00132	0.00110	0.01011	1,212,824	121
100[a]	0.00087	0.004413	0.00101	0.00069	0.00698	837,947	84
110[b]	0.00111	0.007072	0.00138	0.00118	0.01074	1,288,548	129
125[c]	0.00146	0.010931	0.00190	0.00188	0.01618	1,941,125	194
175[d]	0.00265	0.022673	0.00340	0.00390	0.03262	3,914,234	391
200[e]	0.00324	0.027896	0.00401	0.00472	0.03987	4,784,164	478

Note: — = not applicable.

a) IRI level for adequate smooth pavement of Interstate highways.
b) IRI level for adequate smooth pavement of primary roads.
c) IRI level for adequate smooth pavement of secondary roads.
d) IRI level for inadequate smooth pavement of Interstate highways.
e) IRI level for inadequate smooth pavement of primary roads.

2.3 Effects of Roughness on User Safety

Pavement roughness has a direct correlation to road user safety. It alters vehicle handling characteristics and user driving habits. Skidding, reduced steering control, and vehicle bouncing are notable safety hazards attributable to rough pavement surfaces. Below are summaries of two research studies that focused on the relationship between road accident rate and road roughness.

The effects of road features (roughness, skid resistance, and terrain) on user safety are important in roadway design and maintenance. Road roughness and human error can result in accidents. Bester (2003) evaluated the effects of riding quality and road roughness on accident rates in South Africa. Different factors associated with accident rates and severity were considered, including terrain type, riding quality, and different types of accidents. According to Bester (2003), continuous vehicle vibration due to road roughness causes fatigue. Moreover, the suspension movement induced by roughness could be magnified when the road roughness is out of phase with the vehicle suspension frequency, which could lead to cornering problems and inconsistent braking characteristics. Bester (2003) also claimed that potholes alter users' driving habits, causing them to swerve to avoid potholes and potentially lose control of the vehicle. Therefore, the authors concluded that road roughness is influential on vehicle steering capabilities, vehicle braking, and road accidents. This study suggested that the most typical accidents associated with road roughness are loss of control, running off the road and hitting fixed or moving objects. To evaluate the impacts of road roughness on user safety, data related to daily traffic volume, the terrain description, riding quality (PSI), and number of accidents and their severity over a three-year period were collected. It was found that road roughness, shoulder width, and topography affect accident rates simultaneously. Rough roads increase accident rates only in rolling terrains.

A study conducted by Anastasopoulos et al. (2008) quantified the impacts of IRI on accident rates on interstate highways using a Tobit regression analysis technique. This study focused on accident data collected from a highway in Indiana over a five-year period. Anastasopoulos et al. (2008) found that a 27.1 percent decrease in the number of accidents per 100 million vehicle miles travelled (VMT) could be realized if the pavement IRI was kept below 75 inches/mile (1.1 m/km), based on a Tobit regression analysis of the Indiana highway data.

Most of the above studies advocated for a decrease in pavement roughness. Tighe et al. (2000) looked at pavement roughness from another perspective. They reported that 97 percent of all reported fatal and personal-injury accidents occurred on roadways that were in good conditions with low roughness levels, whereas only 1.8 percent of reported fatal accidents and 1.5 percent of reported personal-injury accidents were on roadways with poor conditions. It was concluded that the tendency of drivers to exercise more caution and travel at lower speeds on poor-condition roadways would decrease the number of single-vehicle accidents with high severity on two-way roadways. On the other hand, multiple-vehicle accident rates increase with an increase in roughness level. They proposed that because of road defects, including potholes and improper patching, drivers change their speeds and paths abruptly. Such changes in driving behavior could be the reason for an increase in multiple-vehicles accidents on two-way primary roads. Figure 2.4 shows the relationship between road accident rate and road roughness. Tighe et al. (2000) suggested that to increase safety and to reduce accident rates, IRI should be below 316.8 inches/mile (5 m/km).

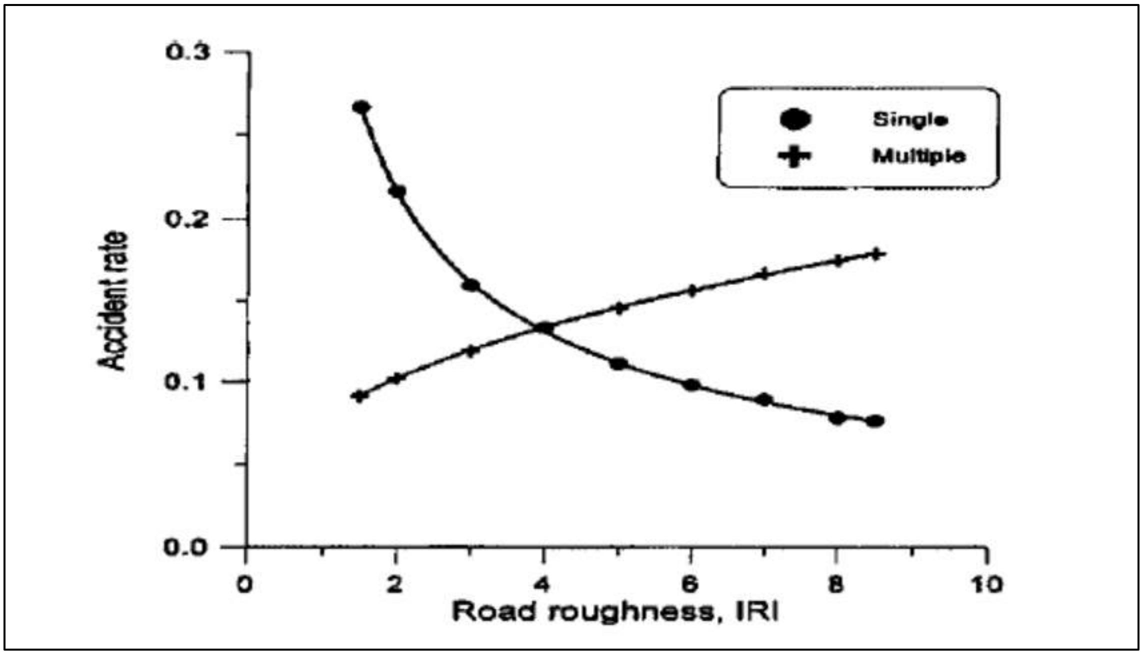

Figure 2.4. Relationship between road accident rate and road roughness (Tighe et al. 2000)

In general, pavement surface roughness creates a safety hazard for all road users. Although roughness may discourage unsafe driving on a per user basis, the uncommon maneuvers that drivers perform give rise to a higher probability of multiple-vehicle accidents. Roughness is also hazardous in the sense that it decreases the effectiveness of vehicle handling characteristics that are necessary for safe driving, such as braking and turning forces. The combination of these road user behavioral and vehicular handling factors means that roughness is a serious problem for roads in the U.S. Therefore, pavement roughness level and user safety should be considered in pavement management along with other important factors that include user and agency costs.

2.4 Pavement Life-Cycle Assessment

Annually, around $160 billion and 320 million metric tons of raw materials are used for activities related to highway construction, maintenance, and rehabilitation in the USA. This significant use of materials requires excessive energy consumption, which results in the production of a vast amount of emissions, including greenhouse gases (GHGs), other air pollutants, and water pollutants, among other environmental impacts (Harvey et al. 2010; Harvey et al. 2014). By applying a life-cycle assessment (LCA), the environmental impacts of pavements can be characterized and quantified. LCA is an approach that assesses environmental impacts, energy consumption, material usage, and other factors contributing to a product system throughout its life cycle, and it quantifies these factors from cradle-to-grave stages. Because of data intensity, LCA should be framed in a systematic and standardized way so that it can be used as a comprehensive and accurate pavement analysis technique. As shown in figure 2.5, pavement LCA includes five phases: 1) material production, 2) construction, 3) usage, 4) maintenance (recycled pavement materials are used in this phase), and 5) end of life (Santero et al. 2011). Using LCA combined with life-cycle cost analysis (LCCA) leads to the selection of the best pavement type and maintenance/rehabilitation method in single or multiple projects and road networks.

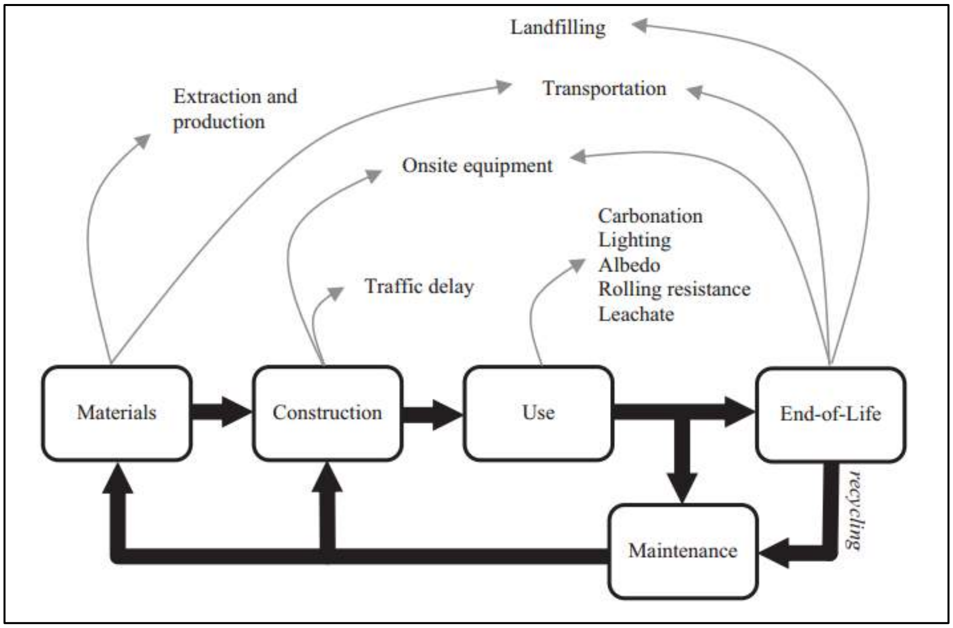

Figure 2.5. Phases and components of the pavement life-cycle (Santero et al. 2011)

There are two methods to perform LCA: 1) a process-based method, and 2) an economic input-output-based method. The process-based method divides each system into individual processes and measures the environmental impacts of each process separately. In this method, boundaries are defined for the LCA system, and emissions for each activity are calculated within those boundaries. Materials used and environmental impacts of each material are evaluated in detail. While creating boundaries makes the model more practical and easier to use, sometimes the choice of boundaries is not clear, leading to elimination of some life cycle impacts of a product or process. On the other hand, the economic-input-output-based method contributes to economic transactions and resource interactions between a set of economic sectors by using the 480*480 input-output matrix of the U.S. economy to recognize the entire chain of suppliers (Hendrickson et al. 2006). In this method, the entire U.S. economy is broken into 480 sectors including transportation, metal production, etc., and inputs and outputs (transactions) from different sectors are measured in dollars.

Most state highway agencies use a single standard rehabilitation method for all pavements in life-cycle assessment on the basis of their historical performance. However, historical data are not representative of the performance of the new design since they are based on old pavement design features (Mack et al. 2014). There are various rehabilitation scenarios that could be applied to pavements, and those scenarios may be different from the method used with the standard LCA, leading to environmental LCA results that do not represent the actual rehabilitation implemented on pavements. Mack et al. (2014) suggested using a decision-making tree analysis to evaluate different rehabilitation methods in LCA. Accordingly, decision trees of different rehabilitation scenarios were developed for Portland cement concrete (PCC) and asphalt concrete (AC) pavements. The probability of occurrence of each activity was assigned on the basis of the Ohio Department of Transportation's (ODOT) suggestions. The expected value of each scenario was then calculated by multiplying the probability of each activity by the global warming potential (GWP) of that activity. By comparing the GWP of standard rehabilitation schedules with different rehabilitation scenarios obtained from the decision tree, the authors concluded that decision-making tree analysis could provide a range of potential GWP instead of a single LCA output. As a result, the associated risk profile of each alternative could be included in the analysis. Consequently, more robust LCAs could be developed.

Incorporating LCA along with LCCA to pavement design and rehabilitation provides more realistic solutions. LCA is important for assessing environmental impacts, energy consumption, materials used, and other factors contributing to a pavement life cycle from cradle to grave. Material production, construction, and use phases of LCA are discussed in the next sections.

2.4.1 Material Production and Construction Phases

Asphalt is a byproduct of petroleum refining, which was estimated to produce 268 million metric tons of energy-related carbon dioxide emissions in 2013 (USEIA 2015). Asphalt production consists of six phases: 1) extraction, 2) transportation and storage, 3) heating, 4) distillation, 5) cooling, and 6) final processing (Zapata and Gambatese 2005). Around 40 percent of energy consumption in the refining process is attributed to bitumen, and the rest is used for lighter products (Stripple 2001). For asphalt concrete mixture production, asphalt is heated to keep its fluidity and mixed with aggregates. Prior to mixing, aggregates are dried by being heated to a temperature of between 150 ^{o}C to 170^{o}C. The final mix is transported to the roadway section for construction.

The USEIA (2015) reported that cement and lime production released around 30 million metric tons of energy-related carbon dioxide emissions in 2013. The energy consumption in the mixing and transportation of PCC are insignificant in comparison to the energy consumption in the production of Portland cement (Zapata and Gambatese 2005). Aggregates do not need to be preheated prior to mixing with cement. Therefore, the major proportion of energy consumption in PCC pavements is related to raw material production for PCC. Even energy consumed in the transportation of raw materials is negligible in comparison to the energy used in production of the cement (Zapata and Gambatese 2005).

Zapata and Gambatese (2005) provided a life-cycle inventory assessment (LCI)[2] on continuously reinforced concrete pavement (CRCP) and asphalt pavement in terms of energy consumption in the construction of roadways. A 1.0-kilometer road section of a two-lane highway (each lane was 3.6-m wide) with high traffic volumes (10 million 80-kN single-axle loads) was selected for this study. The CRCP had a 220-mm thickness with longitudinal and transverse steel reinforcement spaced 100mm and 1.3m on center, respectively. The PCC was designed to have 12 percent cement, 43 percent coarse aggregate, 28 percent fine aggregate, and 17 percent water by weight. The asphalt concrete had a 300-mm thickness with 5 percent asphalt binder content and 95 percent aggregate content by weight. Information about energy consumption attributed to materials was gathered through literature reviews of previous works and interviews with two national heavy-civil construction contractors. Then, the average values of energy consumption were reported for three phases of the pavement life-cycle: 1) raw material extraction and initial material transformation; 2) manufacturing of asphalt, PCC, and rebar; and 3) placement of the materials at the construction site. Results showed that the energy consumed

[2] LCI quantifies and gathers inputs and outputs in life cycle assessment. An LCI can also be conducted as a separate part from LCA (ISO 14040, 2006).

for CRCP and asphalt pavement were around $4.58 * 10^6$ MJ and $3.78 * 10^6$ MJ per kilometer, respectively, showing that CRCP required 21 percent more energy than asphalt pavement over the three phases of the pavement life cycle. However, PCC has a higher average design life than asphalt pavement, so LCCA was conducted to compare the energy consumption of PCC and asphalt pavements. Extraction of raw materials and concrete placement, constituted 6 percent, of total energy consumption for CRCP, cement production constituted 65 percent, steel production 34 percent, and the concrete mixing process 1 percent. For asphalt pavements, extraction of raw materials and asphalt pavement placement, accounted for 8.46 percent of total energy consumed, asphalt mixing and drying of aggregates accounted for 53 percent, production of bitumen 43 percent, and storage 4 percent. These results suggested that energy consumption for the extraction of aggregates and placing of pavement materials were insignificant in comparison to other activities in the procurement of asphalt and PCC concrete surfacings. Note that Zapata and Gambatese (2005) focused only on material production and construction (placing the materials at the construction site) stages, while the contribution of the usage phase to total energy usage was not investigated. Moreover, the benefits of using reclaimed asphalt pavement (RAP) was not considered for asphalt pavements.

2.4.2 Use Phase

The pavement use phase consists of VOCs (additional fuel consumption, tire wear costs and vehicle maintenance costs due to pavement roughness), the heat island effect[3], the non-GHG climate change effect[4], electricity used in roadway lighting, carbonation[5], and water pollution

[3] Due to albedo, a portion of incoming solar radiation reflects back to the surrounding area. Therefore, temperature of metropolitan areas usually become warmer than their surrounding rural areas. Additionally, since pavements trap subsurface water and do not allow it to evaporate, temperature rises even more (Harvey et al. 2010).
[4] High albedo could result in global cooling since only a portion of incoming radiation reflects back to space. This negative radiative forcing can be converted to CO_2 equivalents (Harvey et al. 2010).
[5] "Carbonation occurs when the components of cement, such as $Ca(OH)_2$, react with CO_2 and sequester it in the pavement" (Harvey et al. 2010).

from leachate and runoff (Harvey et al. 2010). It is crucial to assess the costs that contribute to different pavement preservation methods in the life-cycle period of pavements. Below are summaries of previous studies focused on energy use, GHG emissions, and associated costs for the use phase.

Chehovits and Galehouse (2010) evaluated energy usage and GHG emissions of different pavement preservation methods for asphalt concrete pavements. Pavement preservation treatments were compared on the basis of annualized energy usage and GHG emissions within the extended pavement life-time as a result of applied treatments. The results of this study showed that hot mix asphalt (HMA) overlays, hot in-place recycling, new construction, and major rehabilitation had the highest annualized energy use (around 4.9-15.4 MJ/m^2-yr) and the highest GHG emissions (around 0.4-1.3 kg/m^2-yr). Chip seals, micro-surfacing and crack fill exhibited 1.0-3.3 MJ/yd^2-yr energy use and 0.13 to 0.07-0.20 kg/m2-yr GHG emissions per year of extended pavement life. Fog sealing and crack sealing had the lowest annualized energy use, ranging from 0.4 to 1.1 MJ/m^2-yr, and GHG emissions ranging from 0.02 to 0.08 kg/m2-yr. The authors concluded that pavement preservation treatments could reduce energy use and emissions substantially in comparison to conventional rehabilitation and reconstruction methods.

A study carried out by Wang et al. (2013) developed an LCA approach to evaluate the impact of network-level pavement maintenance and rehabilitation methods on GHG emissions and energy use within the California highway network. This study included finding the optimal trigger roughness values (IRI) at which life-cycle energy consumption and GHG emissions were minimized. The cost-effectiveness of implementing the trigger values were considered as well. Three treatment methods were considered: 1) a medium-thickness asphalt overlay on asphalt-surfaced pavement, 2) diamond grinding and concrete slab replacement on concrete-surfaced pavement, and 3) concrete lane replacement. A ten-year analysis period was used. Because of heterogeneity, the network was divided into groups on the basis of traffic levels in order to develop different IRI trigger values for each group. Different IRI trigger values were considered to estimate the optimal trigger value for each group at which the GHG emission reduction would be at a maximum. Results showed that congestion and road gradient had an insignificant effect on changes in fuel economy. In comparison to a “do nothing” scenario (keeping the IRI at or below 279 inches/mile (4.4 m/km) with minimal maintenance of the pavement), implementing optimal trigger IRI values resulted in a GHG reduction of 1.38 MMT and the current California Department of Transportation (Caltrans) IRI trigger value (170 inches/mile [2.68 m/km] on all pavements) resulted in a GHG reduction of 0.57 MMT. Moreover, smoothness achieved after treatment had a significant effect on GHG reduction.

2.5 Decision-Making Tools

Because of the limited budgets of agencies, finding an optimized solution to allocate road maintenance and repair resources is critical. Not only do pavement management approaches influence costs to agencies and users (Li and Madanat 2002; Ouyang and Madanat 2006), but they also have significant environmental impacts (Wang et al. 2013). Below are summaries of previous models and tools developed to find optimal pavement management strategies.

Li and Madanat (2002) suggested a steady-state approach for optimizing the frequency and intensity (thickness) of pavement resurfacing on the basis of the minimum serviceability index (maximum allowable roughness). This approach was created for continuous time and continuous state cases with deterministic pavement deterioration. In the Li and Madanat (2002) study, the pavement condition state represented an infinite time period. The first resurfacing occurred at the trigger point at which the minimum serviceability, or trigger IRI value, was reached. The treatment strategy was considered to be the same for the remaining life of the pavement. This approach did not depend on the initial condition of the pavement, provided that the initial condition had a higher serviceability index than the condition after resurfacing. The purpose of this study was to minimize present value of costs to users and agencies associated with pavement conditions, using the following expressions:

$$\min J=\sum_{n=1}^{\infty}\left\{\int_{t_{n-1}}^{t_n} C\big(s(t)\big)e^{-rt}dt+M(w_n)e^{-rt_n}\right\} \tag{2.1}$$

$$\text{s.t.} \quad \frac{ds(t)}{dt}=F\big(s(t)\big), \tag{2.2}$$

$$s_{2n}-s_{1n}=G(w_n,s_{2n}), \tag{2.3}$$

$$s(0)=s_0 \tag{2.4}$$

where:

J	= present value of agency and user cost,
t_n	= the time of n_{th} resurfacing,
$s(t)$	= the pavement roughness as a function of time,
$C(s(t))$	= the user cost rate as a function of pavement roughness,
w_n	= the intensity (thickness) of n_{th} resurfacing,
$M(w_n)$	= the agency cost as a function of resurfacing intensity,
r	= the discount rate,
$F(s(t))$	= the deterioration as a function of pavement roughness, and
$G(w_n, s_{2n})$	= improvement in pavement condition as a function of resurfacing intensity and pavement roughness immediately before resurfacing.

Pavement deterioration and an increase in roughness (s) were assumed to follow a saw-tooth trajectory (Tsunokawa and Schofer 1994) for every cycle time (τ), as shown in figure 2.6, with a fixed maximum roughness before resurfacing (S_2) and after resurfacing (S_1). This study stated that the discounted life-time cost was not very sensitive to the cycle time (τ), but rather the roughness levels were more influential.

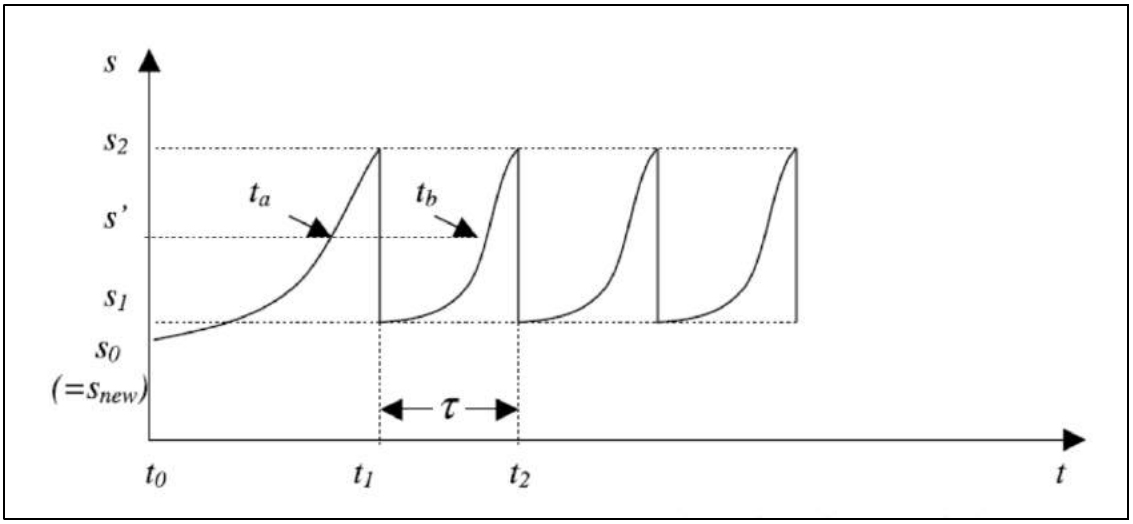

Figure 2.6. System enters the steady state at the time of the first resurfacing (Li and Madanat, 2002)

Sathaye and Madanat (2011) developed an optimized approach for determining the frequency and intensity of resurfacing for multiple highway facilities. This study used deterministic, continuous-state formulation to address performance predictions and maintenance/repair decision-making. Bottom-up pavement management formulation, which considered the heterogeneous facilities, was used. The methodology for solving the problem was formulated as follows:

$$\min \sum_{j=1}^{J} V_j = \sum_{j=1}^{J} \frac{M_j + U_j}{1 - e^{-r\tau_j}} \tag{2.5}$$

$$\text{s.t.} \sum_{j=1}^{J} \frac{M_j}{\tau_j} \leq B \tag{2.6}$$

where:

V_j = Total infinite horizon costs,

M_j = The maintenance cost for a single resurfacing activity,

U_j = User cost incurred between resurfacing activities,

$r < 1$ = The discount rate,

τ_j = The time between overlays, and

B = Agency budget per time for resurfacing activities.

Results for a three-facility network were developed on the basis of the above methodology. The effects of yearly budget (B) on trigger roughness values (s_j^-) and network-level optimal costs ($\sum_{j=1}^{J} V_j$) are shown in figure 2.7 and figure 2.8, respectively. When the yearly budget was low, an increase in budget resulted in a significant decrease in the total costs, and likewise, the trigger roughness values. However, as yearly budget increased, the incremental decrease in total cost and trigger roughness values waned.

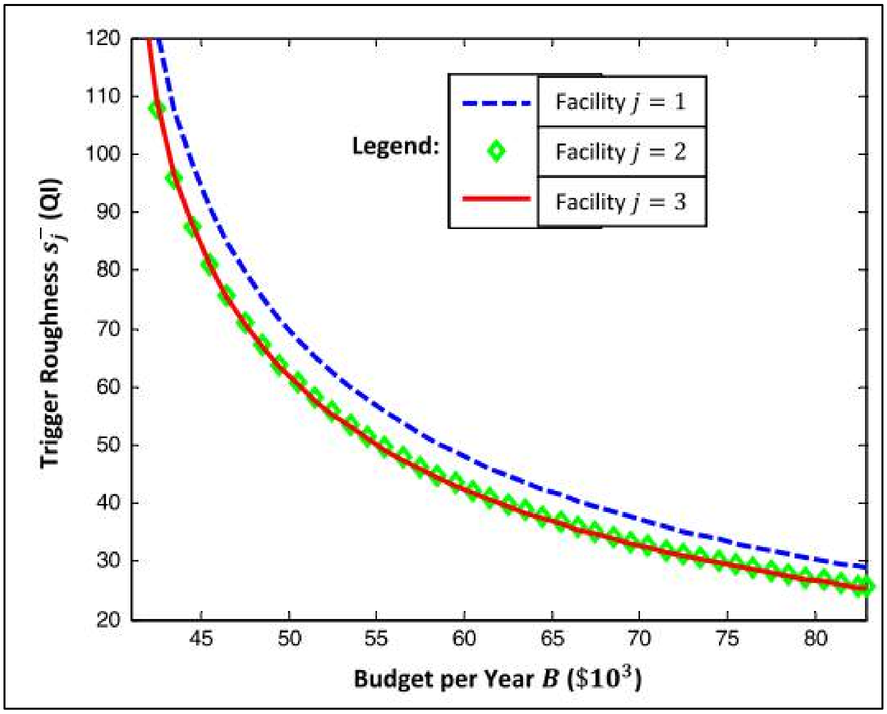

Figure 2.7 Effects of budget on trigger roughness values (Sathaye and Madanat 2011)

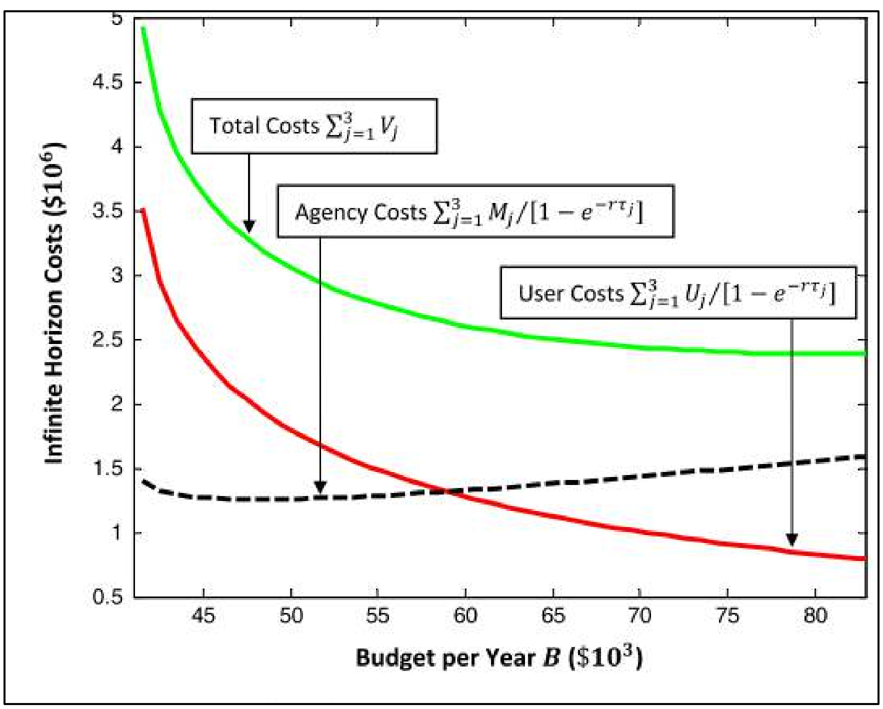

Figure 2.8. Effects of budget on network-level optimal costs (Sathaye and Madanat 2011)

Zhang et al. (2010) developed an LCA-LCCA model, a pavement overlay deterioration model, and a life-cycle optimization (LCO) model to find the optimal overlay preservation method. The LCA model was divided into costs and environmental impacts related to material production, construction, distribution, traffic congestion, usage, and end of life stages (Zhang et al. 2009). The results of the LCA model were used in the LCCA model to estimate agency and user life-cycle costs. In the pavement overlay deterioration model, distress index (DI) was used to predict the pavement performance rather than IRI. The DI is a measurement of pavement condition that includes pavement roughness and deterioration. The LCO model estimated the optimized method for evaluating the energy consumption, environmental impacts, and costs associated with all stages of production and life-cycle. Traffic congestion, traffic growth, overlay deterioration, and pavement roughness impacts were considered in this model as well. Three overlay systems were used, including 1) a concrete overlay with a 175-mm thickness; 2) an engineered cementitious composite (ECC) with a 100-mm thickness, and 3) an HMA overlay with a 190-mm thickness. The objective of this model was to minimize life-cycle burdens (energy consumption, environmental impacts (GHG emissions) and costs to users and agencies). The constraint was to keep the system within a defined performance standard (DI<50) within the 40-year analysis period by using the following expression:

$$B_b[i,j,DI(i)] = \begin{cases} material\,[i,j,DI(i)]w_b^{material} + construction[i,j,DI(i)]w_b^{construction} \\ + distribution[i,j,DI(i)]w_b^{distribution} + congestion[i,j,DI(i)]w_b^{congestion} \\ +usage[i,j,DI(i)]w_b^{usage} + EOL[i,j,DI(i)]w_b^{EOL} & ,if\ i > 0 \\ 0 & ,if\ i = 0 \end{cases} \tag{2.7}$$

where:

b = life cycle energy consumption, GHG emissions, or costs,

i = index of year,

j	= maintenance alternative decisions (0, 1 and 2 mean no action, minor maintenance, and major maintenance, respectively),
DI(i)	= distress index value at year I,
w_b	= life cycle energy consumption, GHG emissions or costs associated with one unit of raw material, utility or process,
$B_b[i, j, DI(i)]$	= burden life-cycle energy consumption, GHG emissions or costs at year i with decision j for one DI value,
$material[i, j, DI(i)]$	= material consumption costs at year i with decision j for one DI value,
$construction[i, j, DI(i)]$	= construction equipment usage at year i with decision j for one DI value,
$distribution[i, j, DI(i)]$	= transportation of materials and equipment at year i with decision j for one DI value,
$congestion[i, j, DI(i)]$	= construction-related traffic congestion at year i with decision j for one DI value,
$usage[i, j, DI(i)]$	= pavement surface roughness impact at year i with decision j for one DI value, and
$EOL[i, j, DI(i)]$	= end of life management of pavement system at year i with decision j for one DI value.

The results showed that, by implementing the optimal strategy, which is shown in figure 2.9, reductions in life-cycle energy consumption of around 5-30 percent, GHG emissions of around 4-40 percent, and costs by 0.4-12 percent could be realized for the three overlay systems in comparison to conventional Michigan Department of Transportation (MDOT) preservation strategies. Moreover, by evaluating the impacts of traffic growth, the authors concluded that this model could create more benefits than the MDOT conventional method. Additionally, they stated that the ECC overlay system had a greater influence on reductions oinf energy consumption, GHG emissions, and costs than concrete and HMA overlays.

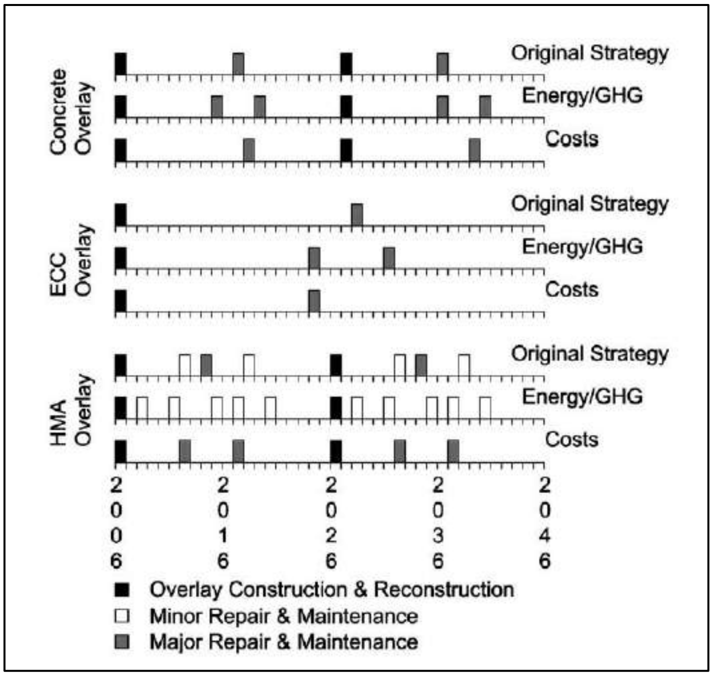

Figure 2.9. Optimal preservation strategies for three overlay systems without considering traffic growth (Zhang et al. 2010)

Chapter 3 Research Methodology

3.1 Analysis of Framework – Code Development

In this study, a prototype, network-level decision-making tool was developed to select the most efficient pavement maintenance and rehabilitation strategies to minimize agency and user costs and maximize their benefits. Field data from 91 roadway sections in Oregon, Idaho, Washington, and California were used to develop and test the developed tool. Field data associated with maintenance history, location, pavement structure, profile, and traffic were obtained from the Federal Highway Administration (FHWA) website (LTPP InfoPave 2016) for all the sections. The data set included previous treatment types, previous treatment thicknesses, annual average daily traffic (AADT), annual average daily truck traffic (AADTT), and the annually collected IRI for the last treatments. Treatment types used in this study were dense graded asphalt concrete (DGAC) overlay, chip seal on dense graded asphalt concrete (DGAC-CS), slurry seal on dense graded asphalt concrete (DGAC-SS), chip seal with modified binder (DGAC-CSMB), asphalt concrete pavement on concrete pavement (CP), asphalt concrete pavement with recycled asphalt pavement (RAP) on concrete pavement (CPR), central plant mixed and cold-laid[6] RAP (RAPCL), central plant mixed and hot-laid[7] RAP (RAPHL), and open-graded asphalt concrete pavement (OGAC). The pavement history and structures for each section are presented in Appendix A in detail.

In this study, pavement conditions were evaluated over a 40-year analysis period. Traffic data in terms of AADTT and AADT for the past years were used to develop linear models to predict the traffic for each section over the analysis period. Having annually collected IRI data

[6] Placement temperatures below 175 ºF

[7] Placement temperatures above 175 ºF

for the past years and treatments, nonlinear models were developed to predict the pavement performance in terms of IRI for each section. To find the optimal budget allocation for pavement maintenance and rehabilitation, a code was developed using MATLAB 2016. The general framework for the decision-making tool development is shown in figure 3.1. Data corresponding to traffic, treatment types and thicknesses, annual IRI, and material and construction costs were used as inputs to the software. For each section, IRI and the net present value (NPV) of user benefits were estimated for each year. If the estimated IRI reached the trigger IRI, a treatment was applied and the NPV of agency cost was estimated. If the predicted IRI was less than the trigger IRI, a “do nothing” scenario was chosen, and the IRI for the next year was predicted for the existing treatment type. This procedure was continued until the 40-year analysis period had been reached. Given agency costs and user benefits based on the treatment types and the frequency of resurfacing of each section, sections were then ranked according to benefit-to-cost (B/C) ratios over the analysis period. Subsequently, the available budget was allocated to the sections with highest priority for treatment (sections with higher B/C ratios). This process was continued until the budget was expended.

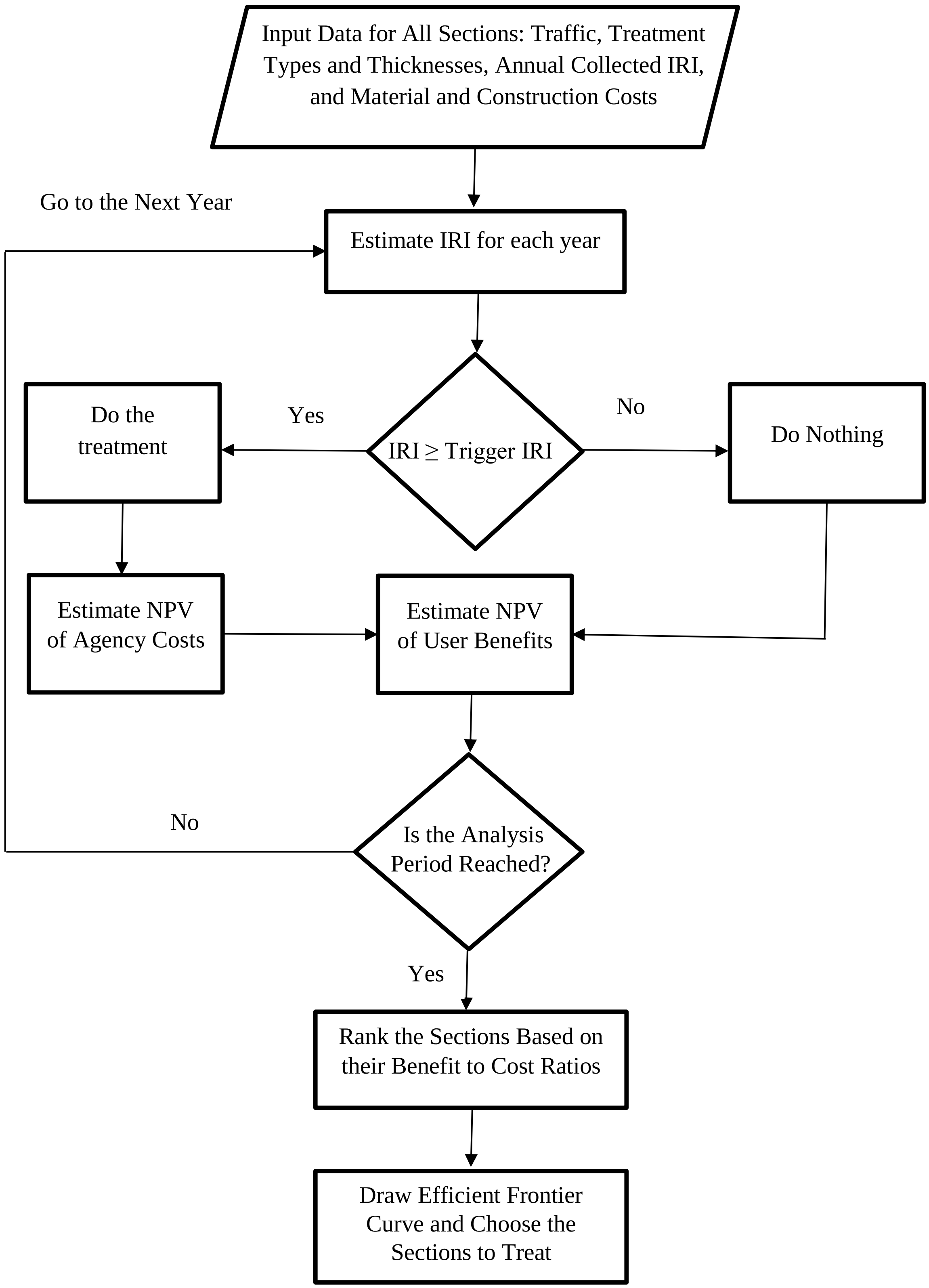

Figure 3.1. Flowchart of procedure to develop the decision-making tool (MATLAB code)

The steps followed for model development are as follows. Each step is discussed in detail in Section 3.2.

1. Traffic data in terms of AADTT and AADT for the approximate 40 years (from 1970s to 2010s) were used to develop linear models to predict traffic for each section over the 40-year analysis period.
2. Annually collected IRI data for the last applied treatment were used to develop nonlinear models to predict pavement performance in terms of IRI for each section over the 40-year analysis period.
3. Data corresponding to traffic, treatment types and thicknesses, annual IRI, and material and construction costs were used as inputs to the software.
4. Pavement performance in terms of IRI was predicted for each section on the basis of the nonlinear IRI models developed in Step 2 after new treatment.
5. Failure points, at which the treatments were applied, were determined over the analysis period for each section.
6. Initial IRIs after each treatment were estimated.
7. The NPV of agency costs (traffic handling, materials, lane closure, and labor and equipment costs) were estimated for each section according to their treatment types and layer thicknesses.
8. Given the failure points for each section, the NPV of user benefits was calculated over the analysis period.
9. Sections were ranked and selected for treatment on the basis of their B/C ratios, and an efficient frontier curve was developed. The priority for treatment was given to the

sections with higher B/C ratios. This process was continued until the budget was expended.

3.2 Steps Followed for Model Development

Field data from 91 roadway sections in Oregon, Idaho, Washington, and California were used to develop and test the decision-making tool. Field data associated with history, pavement structure, profile, and traffic were obtained from the FHWA website LTPP InfoPave (2016) for all the sections. Below is a description of each step followed for model development.

3.2.1 Step 1 – LTPP Traffic Data

Traffic levels, as dependent variables, were categorized into two groups (AADTT and AADT) and were linearly correlated with year, the independent variable. The traffic equation is shown below:

$$\text{Traffic} = a + b * \text{Year} \tag{3.1}$$

where:

Traffic = Traffic level in terms of AADTT or AADT

Year = Number of years since the last treatment was applied

a = Initial AADTT or AADT

b = Coefficient indicating the rate of change of traffic over each year

For the expressions above, coefficients *a* and *b* were estimated over the analysis period for all the sections by conducting a linear regression in software RStudio 2015.

Figure 3.2 shows an example of AADTT versus year for a section in Washington where chip seal was the last treatment. The AADTT data were annually gathered from 1973 to 2009. As illustrated, the linear model was fitted to the data as follows:

$$AADTT=54.72+7.697*Year \tag{3.2}$$

The last treatment (chip seal) was applied in the year of 1990. To predict the AADTT over the 40-year analysis period, the base year was considered to be 1990. Therefore, coefficient *a* was shifted to 185.57 from 54.72.

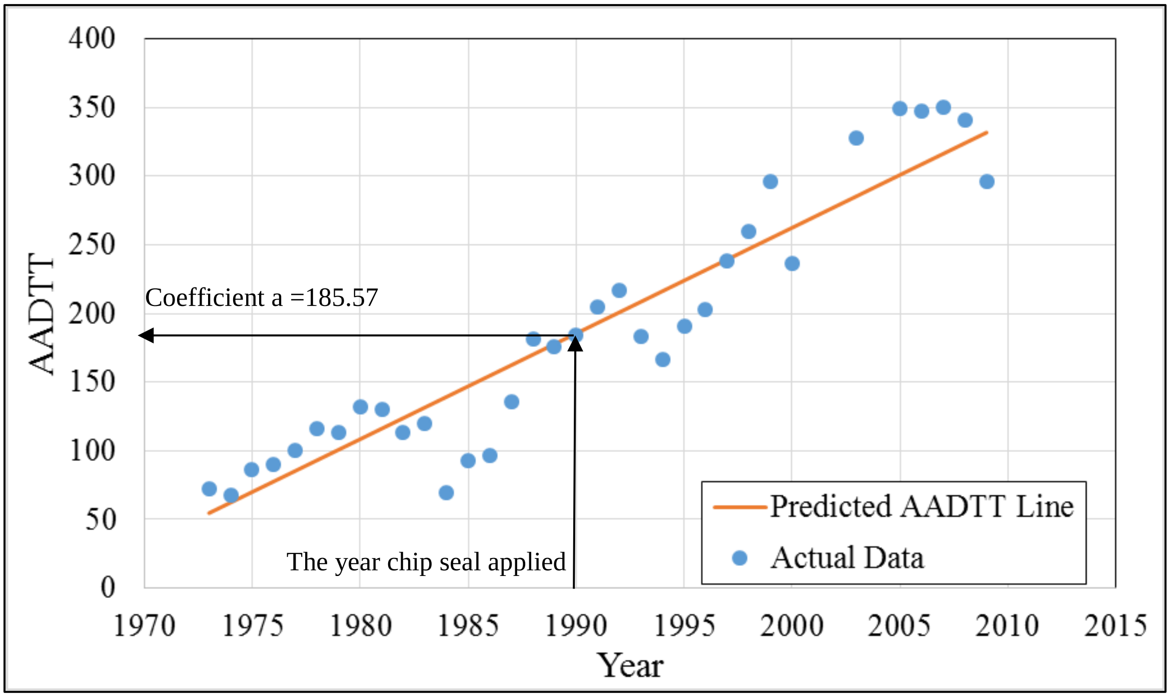

Figure 3.2. Example of AADTT versus year for a section in Washington where chip seal was the last treatment (WA-C350-DGAC-CS)

3.2.2 Step 2 – LTPP IRI Data

In this study, IRI was considered to be the only pavement performance variable indicating pavement life and failure point. With annually collected IRI data of the last treatments, performance equations for IRI were developed, with the value of IRI for that section in each future year being the dependent variable and the number of years being the independent variable. Figure 3.3 shows the annually collected IRI versus year for all the sections in Oregon.

The performance equation for average IRI was formulated as follows:

$$IRI\ (\frac{m}{km}) = a + b * Age^{c} \tag{3.3}$$

where:

IRI = Average IRI in each year of analysis period

a = Initial IRI

Age = Number of years since the last treatment

b and c = Coefficients indicating the rate of change of IRI in each year

To predict the annual average IRI for each section since the last treatment was applied, coefficients *a*, *b*, and *c* were estimated by performing non-linear regressions with RStudio 2015. The initial IRI depended on the quality of the construction. It was possible to have very rough pavements after construction in the past, but new requirements have forced contractors to achieve roughness levels of 0.95-1.1 m/km (60-70 inches/mile) after construction. In order to make the initial IRIs more consistent and comparable, averages of initial IRIs for chip seals and slurry seals were taken, and their performance equations were shifted to the average value. Similarly, performance equations for overlays were shifted to their average initial IRI. Thus, value *a* in equation (3.3) for chip seal and slurry seal was 1.2814 m/km (81.19 inches/mile) and for overlays was 0.9727 m/km (61.63 inches/mile).

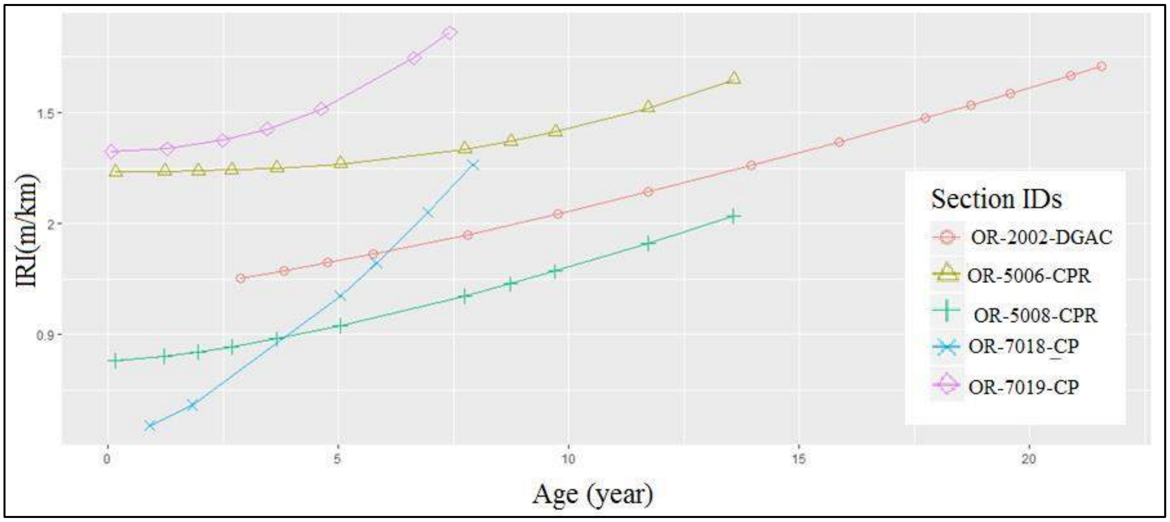

Figure 3.3 Annually collected IRI of the last treatment versus year of the last treatment for all the sections in Oregon

Note:
DGAC: dense graded asphalt concrete.
CP: composite pavement.
CPR: composite pavement having RAP.

3.2.3 Step 3 – Input Data

Data corresponding to treatment types, treatment thicknesses, and material and construction costs were used as inputs to the software. All the data were obtained from the FHWA website LTPP InfoPave (2016). Moreover, coefficients of traffic and IRI equations for each section were input to the software to predict their traffic levels and pavement performance over the analysis period.

3.2.4 Step 4 - Prediction of Pavement Performance (IRI) After New Treatment

To estimate user benefits for each section, the IRI was predicted for new treatments by using the performance equations developed in Step 2. Figure 3.4 shows the predicted IRI versus age for the section in Washington where chip seal was the last treatment. It can be seen that the initial IRI immediately after construction was 0.911 m/km (57.72 inches/mile). The IRI had an increasing trend over time (age). The IRI performance equation for this section was as follows:

$$\text{IRI}\left(\frac{\text{m}}{\text{km}}\right) = 0.911 + 0.0042 * \text{Age}^{2.5349} \tag{3.4}$$

After the performance curves had been predicted, the initial IRIs were shifted to the specified values mentioned in Step 2. For this section, the initial IRI was shifted to 1.2814 m/km (81.19 inches/mile) since chip seal was the applied treatment. A shifted predicted pavement performance curve is also illustrated in Figure 3.4.

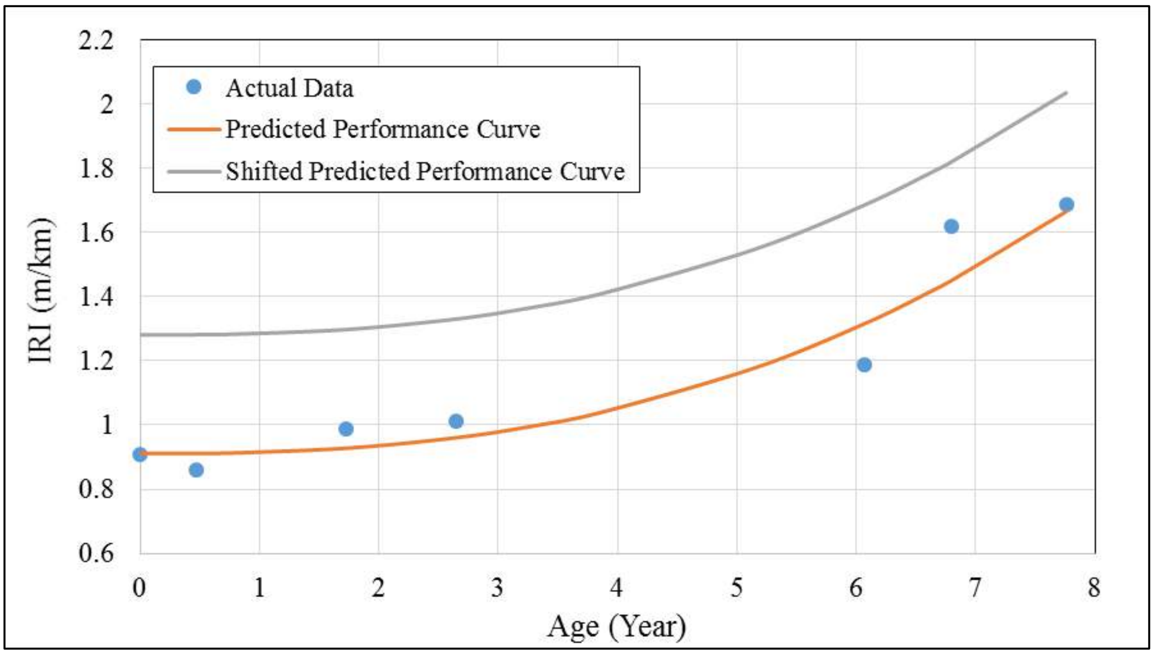

Figure 3.4. Example of performance equation of IRI versus year for a section in Washington where chip seal was the last treatment (WA-C350-DGAC-CS)

3.2.5 Step 5 - Indicating the Failure Points

The IRI was considered to be the only pavement performance variable used to calculate pavement life and failure points. The failure point was defined as the year at which the pavement reached the trigger IRI and the treatment was applied. For a 40-year analysis period, it was assumed that similar treatment types with the same IRI performance were repeated over the analysis period for each section. For instance, if the last treatment had been chip seal, then when the pavement reached its failure point, a chip seal treatment would be applied again, and the application of chip seal would be subsequently repeated over the remaining years in the analysis period to maintain the same pavement performance. Each treatment was applied to reduce IRI to a specified level, and this process is repeated over the 40-year period. Figure 3.5 shows the methodology of this study for finding the frequency of resurfacing and treating a section in California (CA-0504-DGAC) with a dense graded asphalt concrete (DGAC) overlay. As it is presented in figure 3.5, the first failure point was at year 19, and the second treatment occurred at year 38. The trigger IRI was 1.66 m/km (105 inches/mile) for this section. It can be seen that at the year when the trigger IRI was reached, a treatment was applied. The initial IRI right after construction was 0.9727 inches/mile (61.63 inches/mile). The IRI performance equations determined in Step 2 were used to estimate the annual IRI in this step.

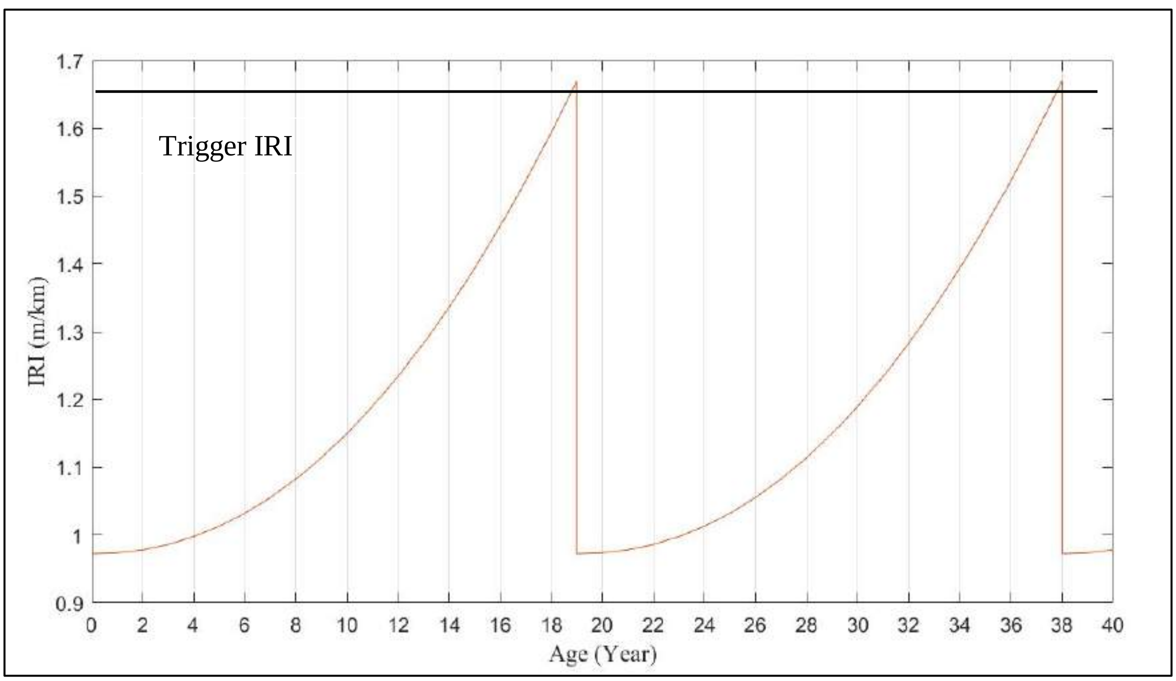

Figure 3.5. Example of the approach for obtaining the frequency of resurfacing and treatment for the CA-0504-DGAC section

3.2.6 Step 6 - Finding the IRI after Each Treatment

The average decrease in pavement IRI after application of chip seal and slurry seal is around 20 inches/mile, for a thin overlay (<0.1 ft) it is 0.71 m/km (45 inches/mile); for a medium overlay (≥0.1 ft and ≤ 0.25 ft) it is 0.95 m/km (60 inches/mile); and for a thick overlay (>0.25 ft) it is 1.58 m/km (100 inches/mile) (Harvey et al. 2010; Harvey et al. 2014) After each treatment, the maximum of the actual IRI and decreased IRI was taken as the initial IRI. For instance, if the trigger IRI was 177 inches/mile, then application of a thin overlay reduced the IRI to 177-45=132 inches/mile. LTPP IRI data showed the average initial IRI (actual IRI) for overlays to be 61.63 inches/mile (0.973 m/km). Thus, the maximum of these two numbers (132 inches/mile) was taken as the initial IRI for this treatment.

3.2.7 Step 7 - Calculating the Net Present Value (NPV) of Agency Costs

Agency costs comprised material, equipment, total labor, traffic handling, and lane closure costs, which are described as follows:

<u>Material Costs</u>

In this study, each section was assumed to be a single-lane with a width of 3.7 m and a length of 1 km, and material costs were calculated for all the sections on the basis of their treatment types and thicknesses.

The unit costs of the materials for slurry seal, dense-graded asphalt concrete, and open-graded asphalt concrete were obtained from the California Business, Transportation and Housing Agency/California State Transportation Agency contract cost data (2015). The average price per unit (tonne) of the materials was estimated on the basis of their quantity per project. Figure 3.6 shows the average price per unit (tonne) versus quantity per project for OGAC. The dashed line represents the fitted power curve to the data. The fitted curve is shown in equation (3.5) . Coefficients *a* and *b* were estimated to be 640.12 and -0.239, respectively, for OGAC.

$$\text{Average price per unit (tonne)} = a * \text{quantity per project}^{b} \tag{3.5}$$

Then, total material costs were estimated for each section on the basis of the quantity of materials used for treatment. For instance, total quantity of OGAC was calculated, and equation (3.5) was used to predict the average price per unit (tonne) of OGAC. Total OGAC costs were estimated by multiplying the average price per unit (tonne) by the total OGAC used for treatment. The volume of the materials used for treating and resurfacing each section was estimated on the basis of the treatment thicknesses and section assumptions described above. To calculate the quantity of materials in tonnes, densities of 2.4 kg/m^3 for DGAC, 2.2 kg/m^3 for OGAC, and 1.2 kg/m^3 for slurry seal were considered, .

Using RAP materials varying between 20 percent and 50 percent could result in cost savings ranging from 14 percent to 34 percent in comparison with use of HMA (Hossain et al. 2012). To estimate material costs for sections with RAP, it was assumed that using RAP would reduce material costs by around 20 percent. The average costs of chip seal application were reported to be \$2.50 to \$5.00 per square yard (Stroup-Gardiner et al. 2009). In this study, the cost associated with chip seal was assumed to be \$3 per square yard and with chip seal with modified binder to be \$5 dollars per square yard.

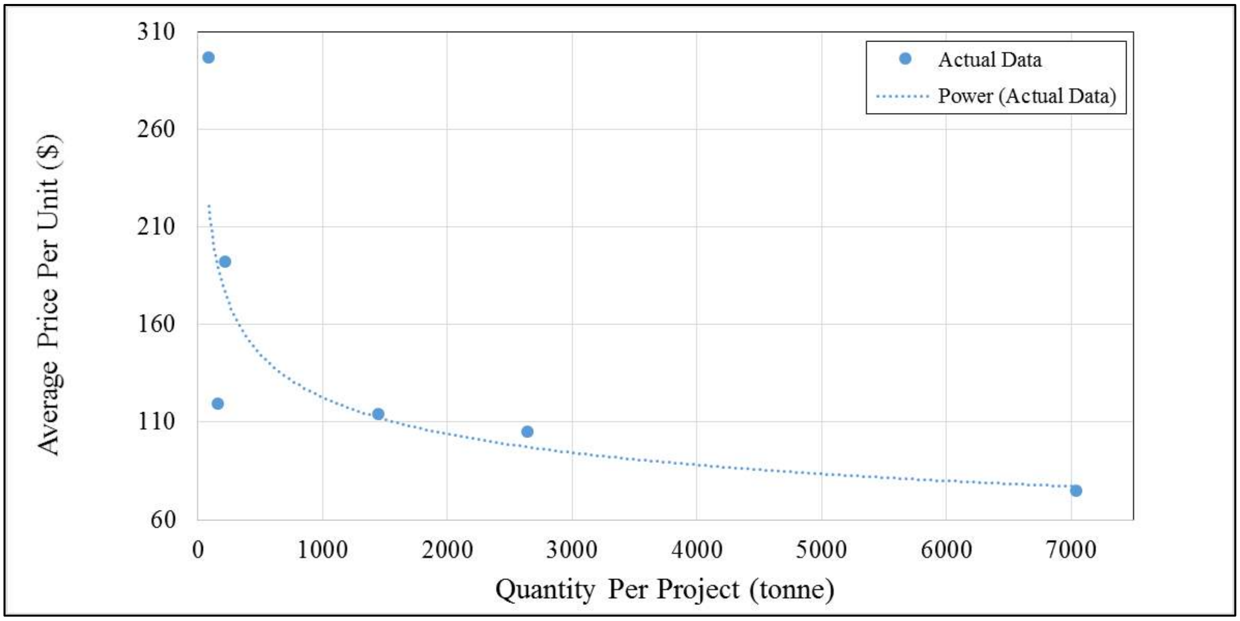

Figure 3.6. Average price per unit tonne of DGAC versus quantity per project

<u>Traffic Handling, Lane Closure, Labor, and Equipment Costs</u>

Costs corresponding to lane closure and traffic handling were considered to be $4000 \ per day (Caltrans 2013). The North Carolina Department of Transportation (NCDOT) (2014) has reported the rate of application of asphalt pavement to be around 200 to 500 tons/day. In order to estimate operation days, lane closure, and traffic handling costs, a rate of application of 500 tons/day was assumed for overlays. The chip seal process is generally accomplished in one day for one kilometer section. Therefore, a one-day closure lane was estimated for chip seal applications.

On the basis of the data obtained from Berkeley Lab (Berkeley Lab 2017), equipment and total labor costs for different treatments were estimated by using the following relationships:

1) Slurry seal: 0.38 *(total construction costs including material costs);
2) Chip seal: 0.39*(total construction costs including material costs);
3) Overlay: 0.19*(total construction costs including material costs).

Total agency costs were calculated by summing up the equipment, total labor, material, traffic handling, and lane closure costs. After \ the failure points were found, agency costs were estimated for each year at which the treatment was applied. The NPV of agency costs was determined afterwards by applying a 4 percent interest rate with equation (3.6) . At the end of the analysis period, the NPV of the salvage value of the pavements was computed as an agency benefit and added to the NPV of agency costs.

$$NPV = \sum_{t=0}^{T} \frac{C_t}{(1+r)^t} \tag{3.6}$$

where:

C_t = estimated user benefit or agency costs at year t,
r = interest rate, and
T = number of time periods.

3.2.8 Step 8 - Calculating Net Present Value (NPV) of User Benefits

Road-user costs were calculated from the total user-cost equations developed in the World Bank's HDM4 models (Bennett and Greenwood 2003). These equations give higher priority for road maintenance and rehabilitation to roads with a greater percentages of trucks. Three-axle trucks and passenger cars were two vehicle classes considered in this study. A 4 percent interest rate was used to estimate the NPV of user benefits. The NPV was calculated by using the Equation (3.6) .

User benefit was estimated as the difference in road user costs between IRI after treatment and maximum IRI (IRI_{max}). User benefit was weighted for traffic volume by multiplying user costs by the number of vehicles (trucks and passenger cars) using the lane. In this study, IRI_{max} was considered to be 5.05 m/km (320 inches/mile), since the suggested maximum trigger IRI for all the sections was 5 m/km (316.8 inches/mile) (an IRI limit for user safety) (Tighe et al. 2000). The IRI_{max} should be greater than all the suggested trigger IRI values, which was 5 m/km (320 inches/mile) in this study. Because this study aimed to compare user benefits for different sections with different traffic levels and treatment types, **predicted user benefits were non-monetary**. This approach, however, could appropriately compare user benefits for different strategies. Moreover, the cost equations from HDM4 models were not adjusted for inflation and they were not the actual costs. Figure 3.7 shows how the user benefit was calculated. The difference in user costs between IRI_{max} and IRI after treatment was estimated for each year (presented as vectors in Figure 3.7). Then, weighted user benefits at each year were converted to NPV and summed up to find the total benefits of applying the treatment.

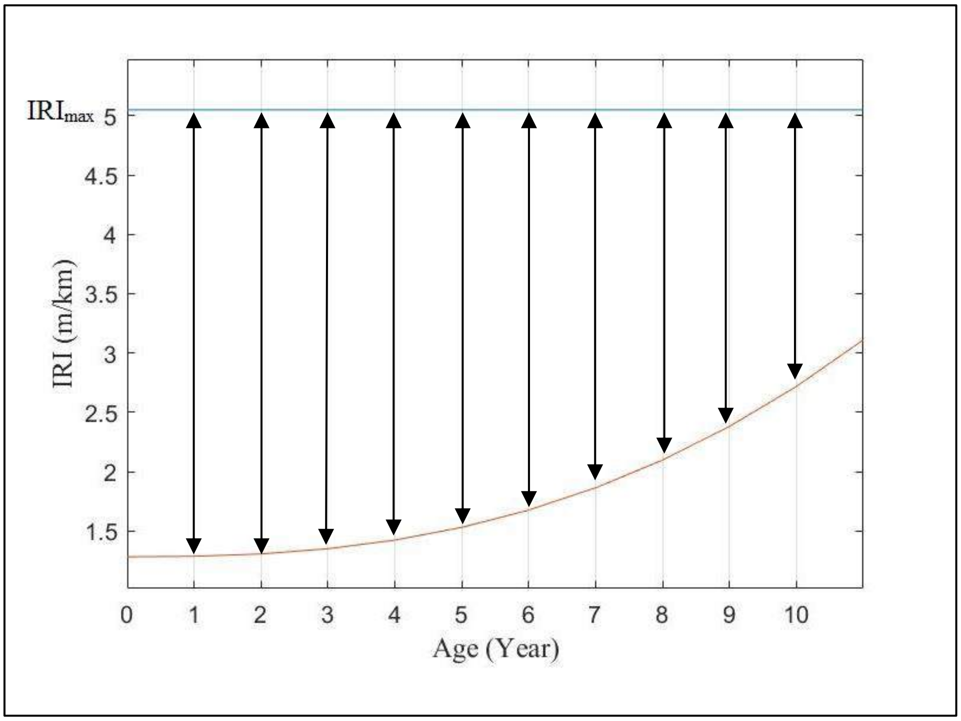

Figure 3.7. Illustration of user benefits for a section in Washington where chip seal was the last treatment (WA-C350-DGAC-CS)

3.2.9 Step 9 - Efficient Frontier Curve

Development of an efficient frontier curve can be depicted by a plot of cumulative benefit versus cumulative cost for all the sections. The arrow showing benefits and costs of the section with the highest B/C ratio comes first on the plot. The arrows of benefits and costs of other sections are connected end-to-end in order of decreasing B/C ratio. This plot is called the "efficient frontier curve" (Merton 1972; Mbwana 2001), and it is presented in figure 3.8. After the efficient frontier curve has been plotted, sections with the highest B/C ratios can be selected for maintenance and rehabilitation with the current available budget. For the example given in figure 3.8, if the available budget is $\$2.8 * 10^5$, sections CA-2051-DGAC, CA-8150-DGAC, WA-6048-RAPHL, and CA-0567-OGAC should be selected for maintenance. Additionally, budget required to achieve a specific benefit level can be estimated by using the developed efficient frontier curve. User benefits and required budgets associated with treating the sections are presented in table 3.1 in tabular form.

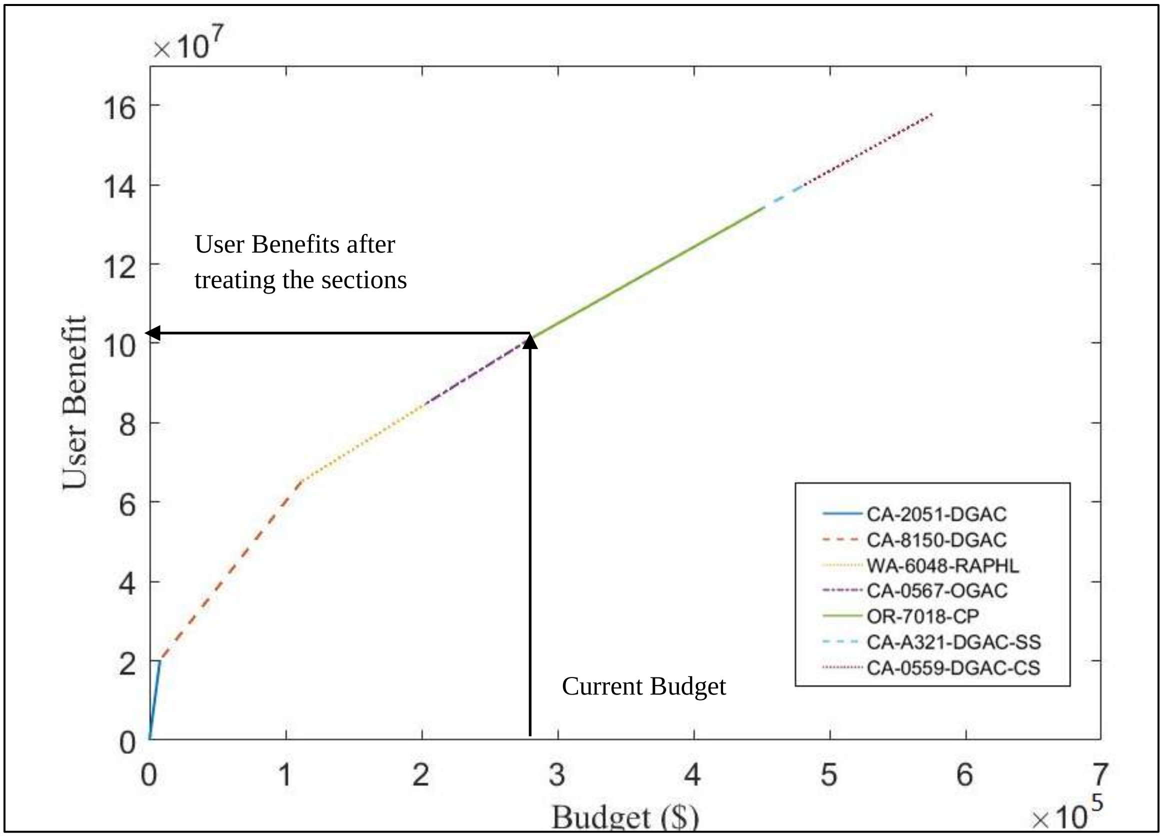

Figure 3.8. Illustration of efficient frontier curve for seven sections of this study

Table 3.1. The user benefits, available budget, and B/C ratios of seven sections

Section IDs	User Benefits	Budget ($)	B/C
CA-2051-DGAC	20,180,862	7,750	2,604
CA-8150-DGAC	45,008,923	104,072	432
WA-6048-RAPHL	19,685,652	91,873	214
CA-0567-OGAC	16,382,191	77,000	213
OR-7018-CP	32,873,537	170,644	193
CA-A321-DGAC-SS	5,514,009	28,700	192

3.3 Methodology for Finding the Trigger IRI by Considering User Safety, User Cost Benefits, and Agency Costs

This study followed two methods to find the trigger IRI and apply the treatments:

1) considering one value for the trigger IRI for all the sections regardless of the traffic levels, and
2) considering different trigger IRIs for sections on the basis of their traffic levels (Madanat 2014).

The first approach considered one value for the trigger IRI for all the sections regardless of the traffic levels. As the IRI reached that trigger IRI, a treatment was applied and the IRI was reduced to a certain value. For example, if the trigger IRI was assumed to be 177 inches/mile, the failure point for all the sections was when the IRI reached 177 inches/mile over the analysis period.

The second approach follows with Madanat (2014) method. Sathaye and Madanat (2011) suggested the use of different trigger IRI values for different traffic levels (figure 3.9). Suggested trigger IRIs for different traffic levels were as follows:

- Trigger IRI = 1.6 m/km (101 inches/mile) for the 30 percent of the roadway network with the highest traffic (top 30 percent traffic volume)
- Trigger IRI = 2 to 2.8 m/km (127 to 177 inches/mile) for the 25 percent to 70 percent of the roadway network traffic (medium traffic level)
- Trigger IRI = 5 m/km (316.8 inches/mile) for 25 percent of roadway network with the lowest traffic (lowest 25 percent traffic volume).

Tighe et al. (2000) suggested that to increase safety and to reduce accident rates, the IRI should be below 5 m/km (316.8 inches/mile). Therefore, this study considered a trigger IRI of 5 m/km (316.8 inches/mile) for the lowest 25 percent of network traffic level. Following the procedure developed by Madanat (2014), sections were ranked on the basis of their traffic levels, and trigger IRIs were assigned to sections according to their traffic levels in the network.

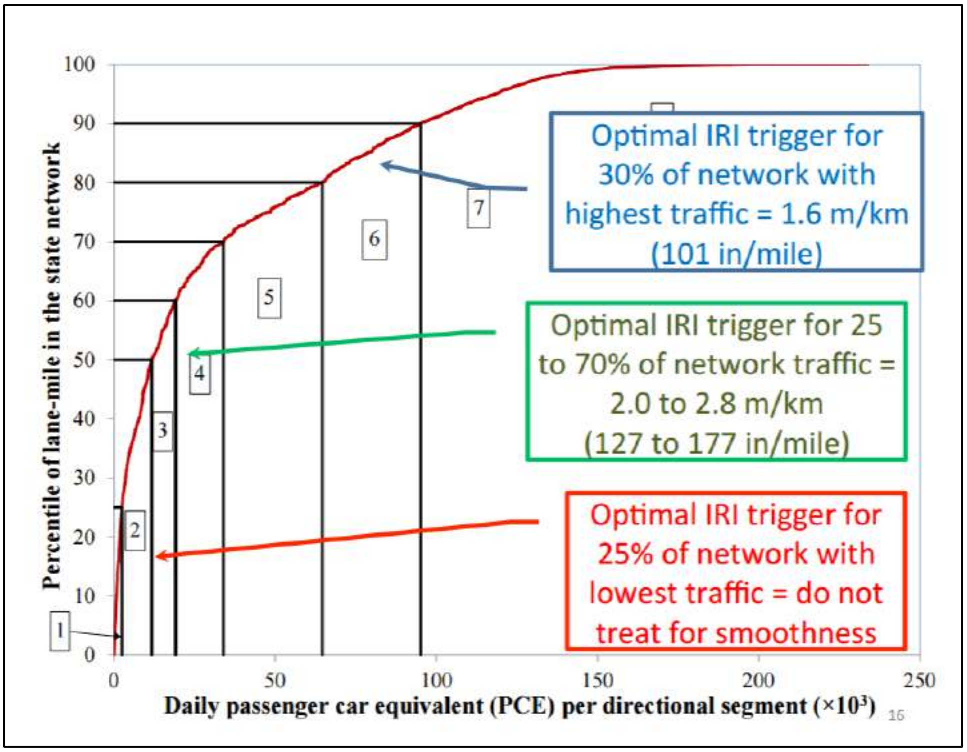

Figure 3.9. Optimal trigger IRI for different traffic levels (Madanat 2014)

Chapter 4 Results and Discussion

The decision-making tool was developed for two trigger IRI methods discussed in the previous section. The results were as follows.

4.1 One Value for Trigger IRI

Efficient frontier curves were developed for different trigger IRI values, ranging from 1.42 to 5.05 m/km (90 to 320 inches/mile). As shown in figure 4.1, reducing trigger IRI values increased user benefits but required higher budgets for paving. As the trigger IRI increased, user benefits and required budget for treating and resurfacing the sections both decreased. Figure 4.1 shows that budget levels control the optimal selected IRI levels. For instance, if the available budget was greater than $\$9.5 * 10^6$, then a trigger IRI of 1.58 m/km (100 inches/mile) over the analysis period would create higher user benefits. On the other hand, if the available budget was less than $\$9.5 * 10^6$, then a trigger IRI of 1.74 m/km (110 inches/mile) would result in higher user benefits.

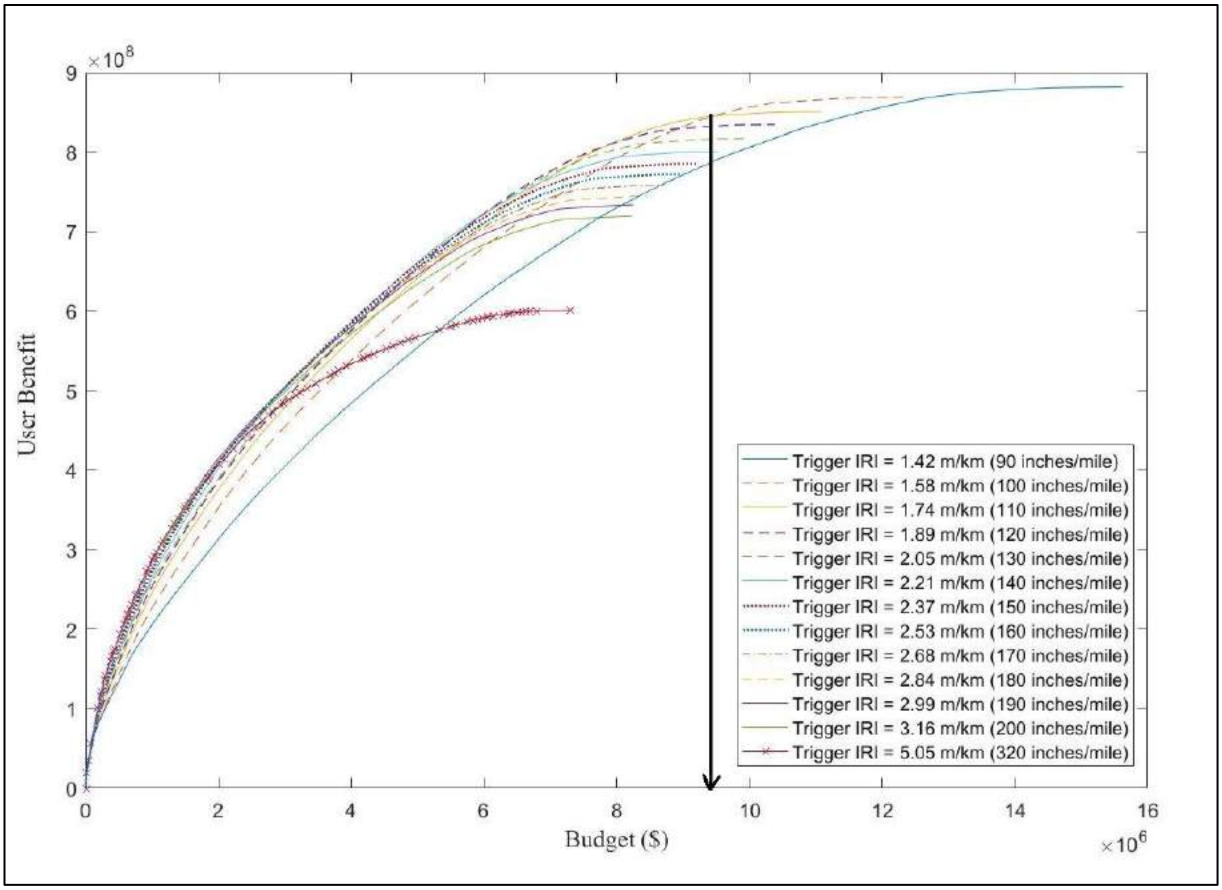

Figure 4.1. Efficient frontier curves for different values of trigger IRI regardless of traffic levels

4.2 Different Trigger IRI Values Based on Traffic Levels

Traffic levels were also considered for developing the efficient frontier curve (Sathaye and Madanat 2012). Since different values for the trigger IRI were considered for 25 percent to 70 percent of network traffic, ranging from 2 to 2.8 m/km (127 to 177 inches/mile), the efficient frontier curve was developed for different trigger IRIs for this middle range of traffic. According to Sathaye and Madanat (2012), sections should be ranked on the basis of the daily passenger car equivalent. To estimate the passenger car equivalents of the 3-axle trucks, AADTTs were multiplied by the coefficient of 1.2175 and ranked on the basis of their traffic levels in each year of analysis period (Ahmed, 2010). Optimal trigger IRIs were annually assigned to the sections after each year. Figure 4.2 shows the efficient frontier curve for trigger IRI values of 2 m/km, (127 in/mile), 2.5 m/km (157 in/mile) and 2.8 m/km (177 in/mile). As shown in the figure, a lower trigger IRI for 25 percent to 70 percent of network traffic (medium traffic level) could increase the required budget and user benefits slightly, but not significantly.

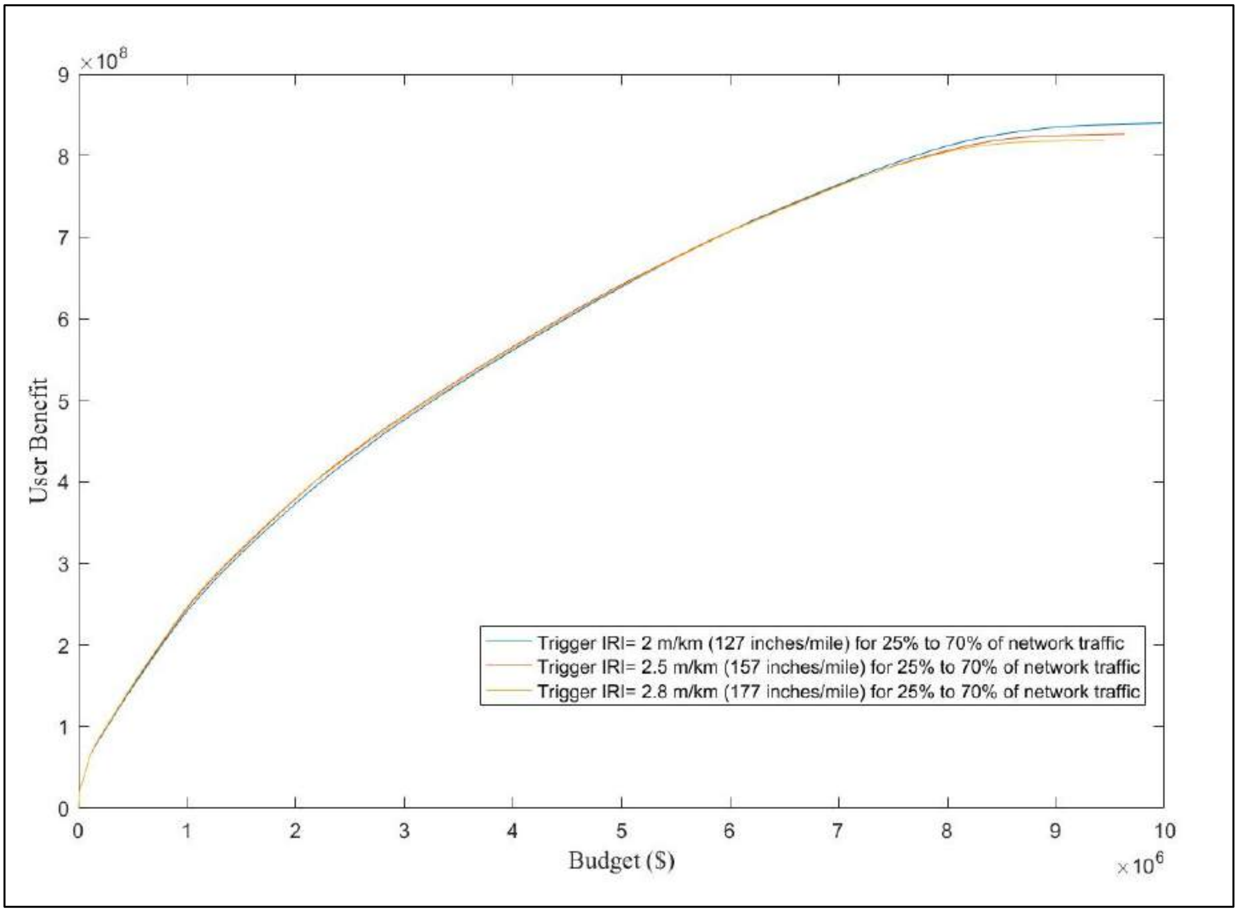

Figure 4.2. Efficient frontier curve for different values of trigger IRI by considering traffic levels

4.3 Optimal Trigger IRI According to the Available Budget

Efficient frontier curves for different values of trigger IRI and different methods were compared: the first using one value for the trigger IRI for all sections regardless of traffic levels (section 4.1) and the second using different trigger IRI values for different traffic levels (section 4.2). Figure 4.3 shows the efficient frontier curves for different scenarios. The “line of maximum benefit for different trigger IRI values” was found in order to find the optimal trigger IRI for different budget levels at which user benefits would be at a maximum. To find the “line of maximum benefit for different trigger IRI values,” the budget level was divided into small intervals, and in each interval maximum user benefit and the corresponding trigger IRI value were determined. Subsequently, the optimal trigger IRI versus budget was plotted, as presented in figure 4.5. It can be seen that as the budget increased, the trigger IRI at which the user benefit was maximal decreased. Figure 4.4 shows that considering one trigger IRI for all the sections regardless of their traffic level provides higher benefits than following the Madanat (2014) method. The suggested trigger IRI for different budget levels is also shown in table 4.1.

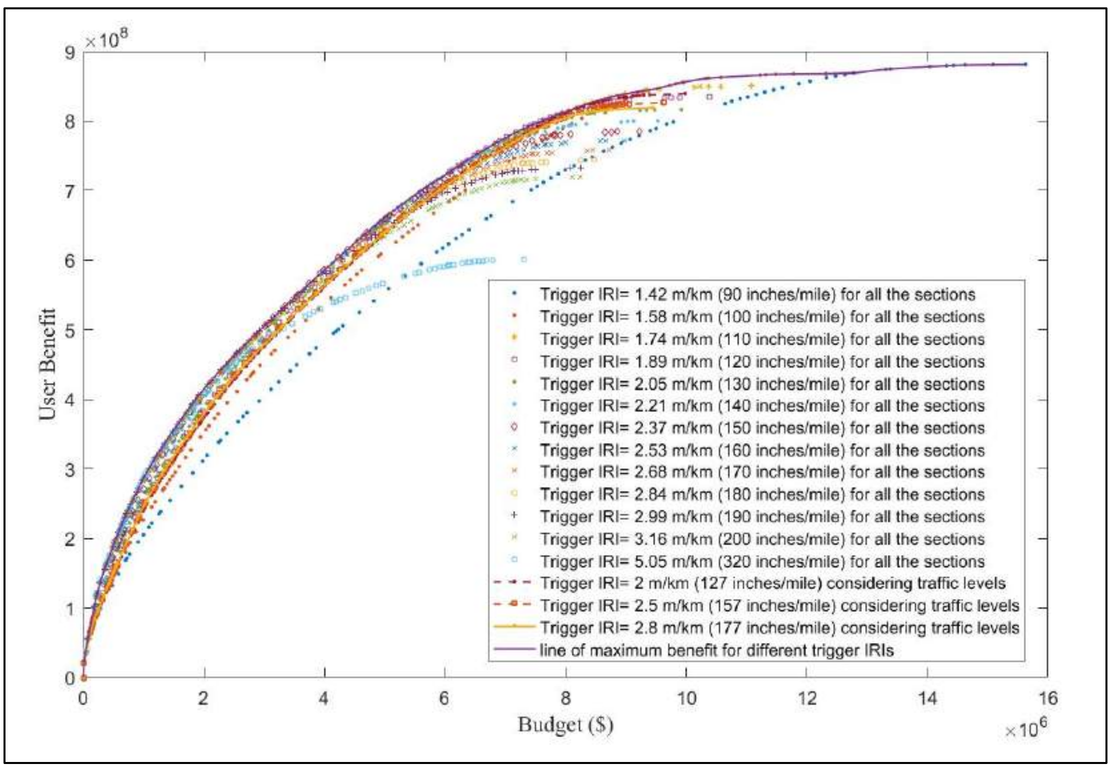

Figure 4.3. Illustration of finding the optimal IRI for different budget levels

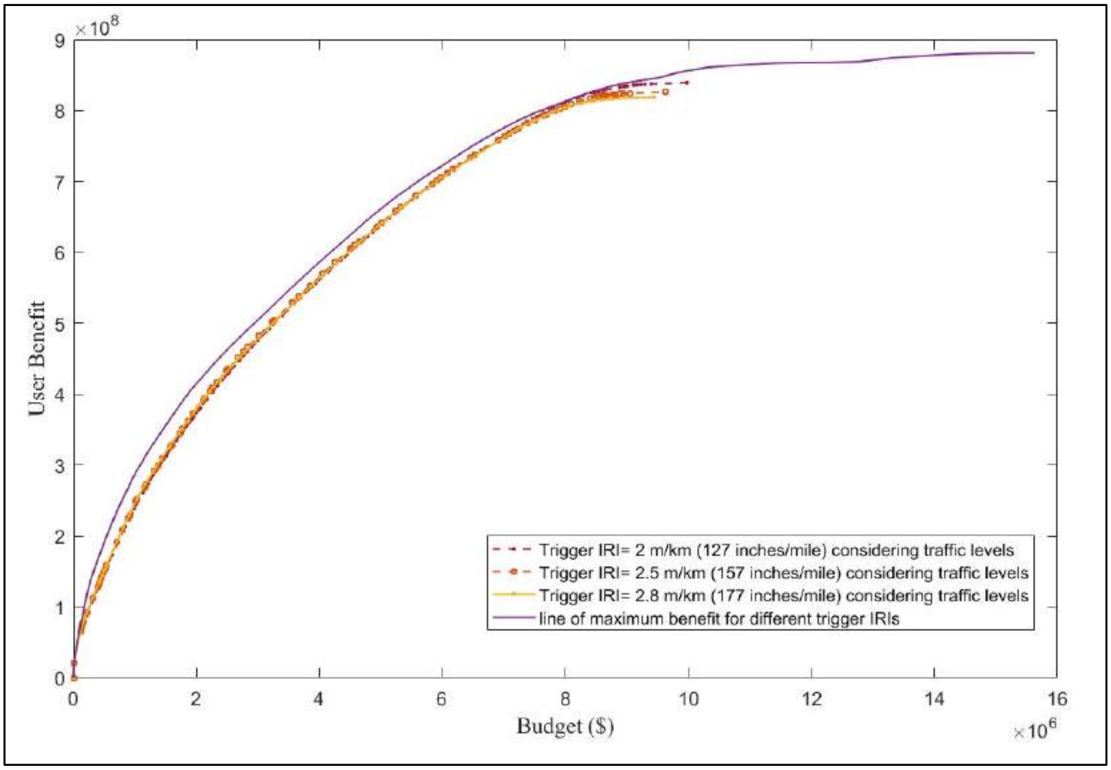

Figure 4.4. Illustration of optimal IRI for different budget levels and efficient frontier curve for different values of trigger IRI by considering traffic levels

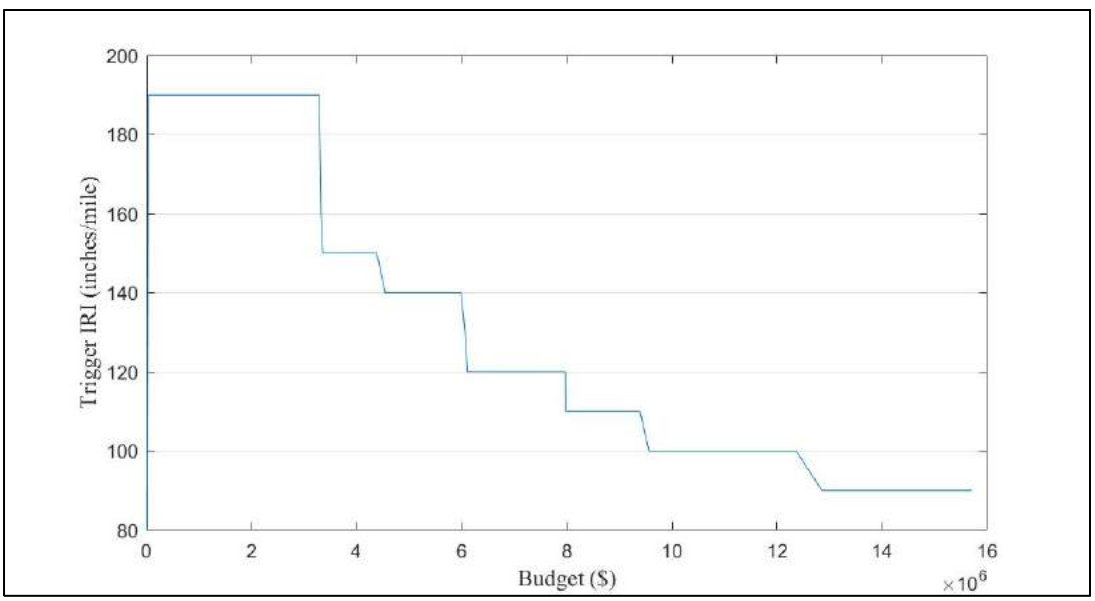

Figure 4.5. Optimal trigger IRI versus agency costs (budget)

Table 4.1. Suggested optimal trigger IRI for different budget levels

Trigger IRI (inches/mile)	Budget ($)	
	from	to
Value of trigger IRI does not matter	0	7.75E+03
190	7.75E+03	3.28E+06
160	3.28E+06	3.32E+06
150	3.32E+06	4.38E+06
140	4.38E+06	5.90E+06
140	5.90E+06	5.98E+06
130	5.98E+06	6.06E+06
120	6.06E+06	7.97E+06
110	7.97E+06	9.39E+06
100	9.39E+06	1.24E+07
90	1.24E+07	1.57E+07

Chapter 5 Integration of the Developed Decision-Making Tool with Geographic Information Systems (GIS)

The network-level decision-making tool is immensely useful for analyzing which roadway sections within the network will provide the most efficient allocation of agency maintenance budgets and yield the most benefit to road users. This tool could be even more useful if the roadway sections were spatially cataloged so that users of the tool could visually analyze which sections are more critical to maintain or rehabilitate. An extension of this tool would integrate f MATLAB code results with a geospatial information systems (GIS) map. Although this was an auxiliary focus of this study, the potential benefits of pursuing a GIS map are discussed below.

GIS is a powerful tool that is used to spatially catalog information. It is incredibly useful for asset management, decision-making, and client outreach in a variety of fields, including transportation engineering. GIS comprises one or more databases that store information about objects of interest that are spatially referenced in a map. This information is stored in data layers, or feature classes, that have attribute tables detailing pertinent information about an object of interest. Information can be stored as point, line, or polygon features within the GIS map. A common software package used in GIS operations is ArcGIS. This software provides an environment that allows users to examine, process, and prepare spatial data efficiently for a variety of purposes. GIS users can query and expand upon information stored in a database readily and easily by using built-in tools within the ArcGIS environment. GIS developers also have the ability to create custom tools that can suit any data processing need. GIS data are easily shareable, meaning that they can be viewed by anyone with GIS software installed on their computer. What is even more powerful is the use of online maps, which involves publishing a

GIS database to an online web server, an inherent function of the ArcGIS software. This way, any interested party can view GIS data easily from within a web browser, eliminating the necessity of having a GIS software license.

The utility of GIS in the framework of pavement management is to allow for accurate and expedient record keeping of past maintenance strategies and easy access to data by multiple stakeholders. Many state DOTs, including Oregon and Utah, have successfully implemented web-based GIS portals that allow interested parties to view and query information about the state's transportation infrastructure (Oregon Department of Transportation 2017; Esri 2015). These maps have valuable information, but for the purposes of this study, they are currently limited by their ability to provide a means of decision-making in terms of choosing maintenance strategies for road sections.

To extend the utility of the network-level decision-making tool developed in this study, a prototype GIS map was created using ArcGIS in order to investigate the feasibility of integrating the results of the decision-making tool with the spatial referencing power of GIS. The goal of the GIS map was to create the ability for users to import LTPP road section data and the tool's MATLAB results into the GIS environment; spatially catalog this information; and then rank, highlight, and export selected roadway sections that present the highest benefit-to-cost ratios, or highest maintenance priority. This output would illustrate which sections should receive maintenance and rehabilitation first for a given budget and trigger IRI value and would show where they were located geographically. It would essentially be a spatial representation of the efficient frontier curve for a given trigger IRI and state's roadway network.

To prove the methodology of the GIS process, 20 sections in the LTPP database, namely five sections in Oregon and 15 sections in Idaho, were selected to spatially catalog. MATLAB outputs for a single trigger IRI of 170 inches/mile were arbitrarily selected as trial subjects. A custom geodatabase was created, and base data for the Oregon and Idaho highway networks was obtained from online geospatial data clearinghouses for each state. A custom feature class, or data layer, containing point features was created for each state in order to import LTPP road section data from Excel spreadsheet files into the respective data layer's attribute table. These feature classes utilized the State Plane coordinate systems of each respective state. The MATLAB code outputs were also imported to these custom feature classes. A custom ArcGIS tool was created with Python scripting that allowed the user to calculate the benefit-to-cost ratios for each road section. Another custom tool was created that ranked each section sequentially based on which benefit-to-cost ratios were greatest.

Figure 5.1 shows the LTPP sections for Oregon spatially cataloged within the GIS map.

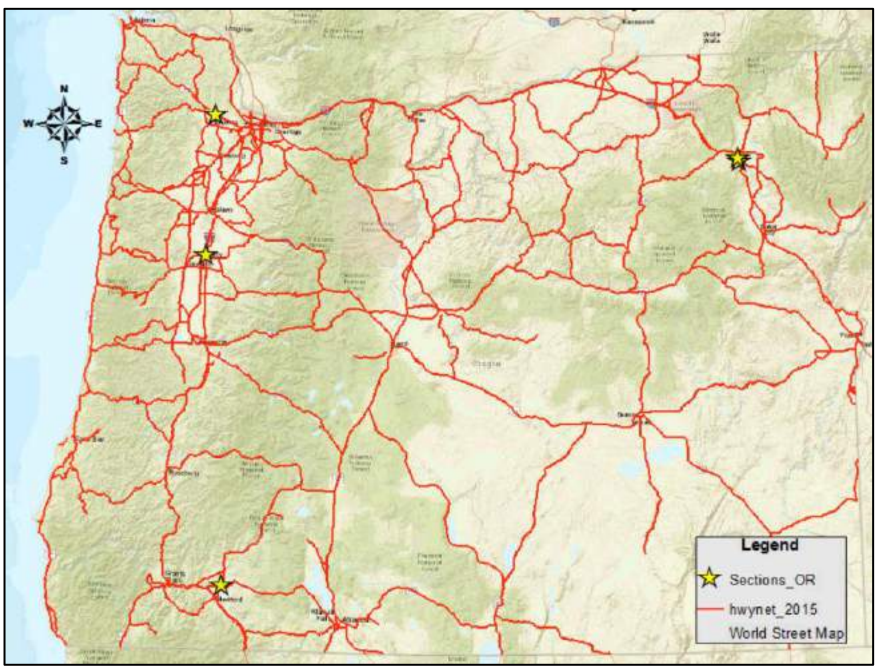

Figure 5.1. Map of Oregon highway network with LTPP sections shown

Table 5.1 shows the attribute table for the Oregon LTPP sections, including imported MATLAB output data, as well as GIS-derived benefit-to-cost ratios and ranking.

Table 5.1. Attribute table for Oregon LTPP sections with MATLAB outputs, benefit-to-cost ratios, and ranking

sectiontreatment	AVGTRUCKTRAFFIC	AVGCARTRAFFIC	USERBENEFIT_TRUCK	USERBENEFIT_CAR	USERBENEFIT_TOTAL	COSTS_MATERIAL	B_C_RATIO	RANK
OR-2002-DGAC	264977	3337035	4187850	11862451	9973219	76733	130	2
OR-5006-CPR	684245	759758	10297796	2714393	8085420	79755	101	3
OR-5008-CPR	645642	698773	9536201	2447826	7446548	78174	95	4
OR-7018-CP	1964753	5266160	26704050	16670134	26951535	109228	247	1
OR-7019-CP	263840	2083715	4019025	6697919	6659216	146267	46	5

Once data processing was complete, the attributes of the point feature classes for Oregon and Idaho were migrated to the highway line features for each state. This was done by using built-in ArcGIS Buffer, Clip and Join functions, which allow the users to select a portion of a data set on the basis of proximity and to copy attribute information to the newly selected features. The resulting data layer was a line feature class comprising 1-km test sections for each LTPP pavement section of interest and containing all MATLAB and efficient frontier curve information previously obtained in the above steps.

Figure 5.2 shows a zoomed-in view of one of the LTPP sections in Oregon, with highway network line data clipped to a 1-km test section.

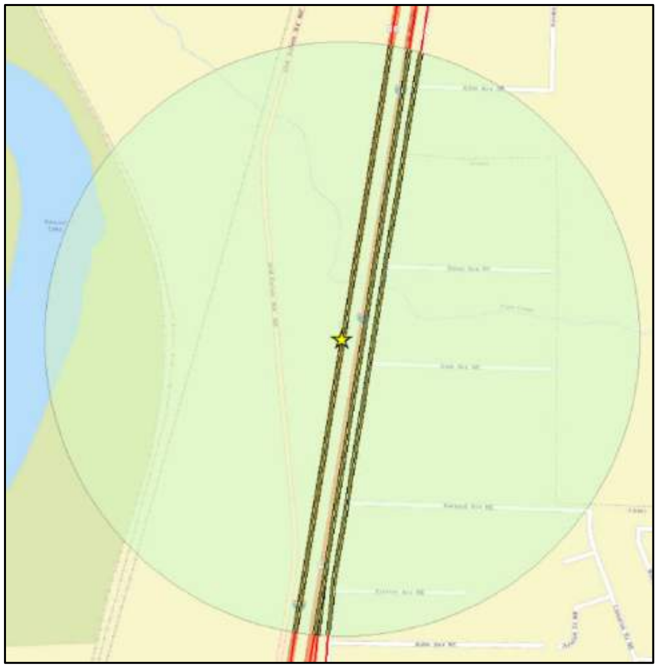

Figure 5.2. Close-up view of Oregon LTPP section with clipped line data

To further integrate the GIS map with the decision-making tool results, all sections that should be maintained on the basis of a given budget were selected in the ArcGIS attribute table based on their benefit-to-cost ratio rankings. This relates to the efficient frontier curve and would essentially allow users to select all road sections that had highest priority for maintenance for a given budget (i.e., all the sections to the left of the budget amount) on the basis of their benefit-to-cost ratios. Then, these sections were exported to a new feature class/data layer by using built-in ArcGIS functionality. This way, the data would be shared with other stakeholders who could easily load the data layer in a GIS environment to see the spatial location of the road sections and all accompanying attribute data in the attribute table.

For instance, consider an example for select LTPP road sections in Oregon and Idaho for a trigger IRI of 170 inches/mile where the available budget was $500,000 for each state. A plot of the efficient frontier curve for both states for this situation is shown in figure 5.3 and figure 5.4.

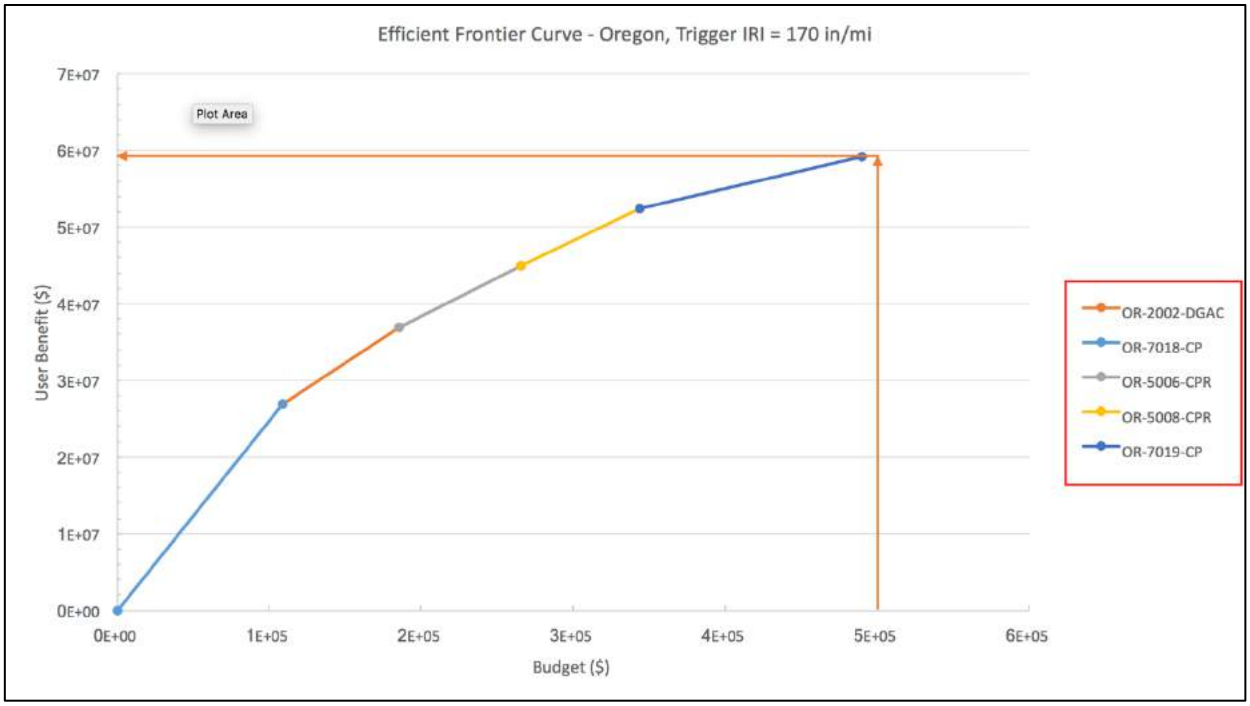

Figure 5.3. Efficient frontier curve for Oregon at an IRI value of 170 inches/mile

As is shown in figure 5.3, the sections in Oregon that could be treated for this budget are OR-2002-DGAC, OR-7018-CP, OR 5006-CPR, OR-5008-CPR and OR-7019-CP. Therefore, for the budget level of $500,000, Oregon could treat all of these LTPP road sections.

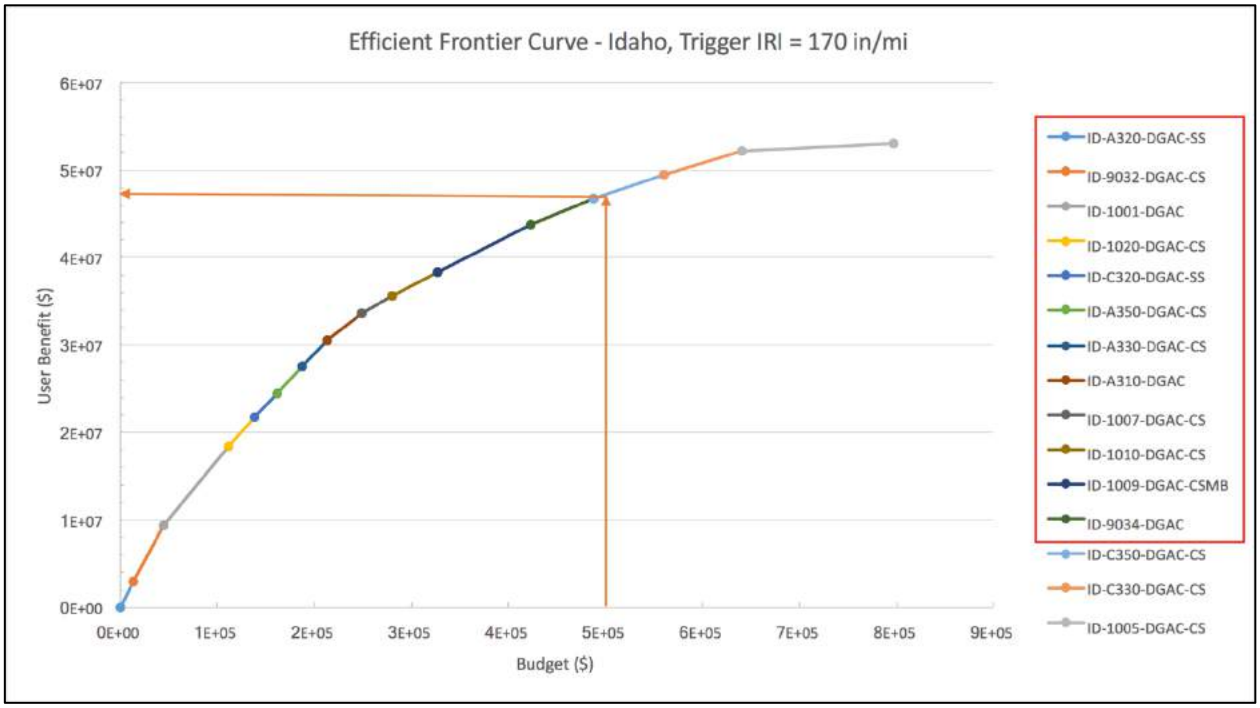

Figure 5.4 Efficient frontier curve for Idaho at an IRI value of 170 inches/mile

As is shown in figure 5.4, the sections in Idaho that could be treated for this budget are ID-A320-DGAC-SS, ID-9032-DGAC-CS, ID-1001-DGAC, ID-1020-DGAC-CS, ID-C320-DGAC-SS, ID-A350-DGAC-CS, ID-A330-DGAC-CS, ID-A310-DGAC, ID-1007-DGAC-CS, ID-1010-DGAC-CS, ID-1009-DGAC-CSMB and ID-9034-DGAC. Therefore, for a budget of $500,000, Idaho could treat these select LTPP road sections.

After obtaining these results from the efficient frontier curve, a user of the GIS tool could then select these particular sections on the GIS map from within the attribute table for each state and export the selection to a new data layer. This data layer representing the highest priority sections to be maintained for a given budget based on benefit-to-cost ratios could be easily shared with other stakeholders and interested parties.

Figure 5.5 shows a methodology flowchart for GIS operations.

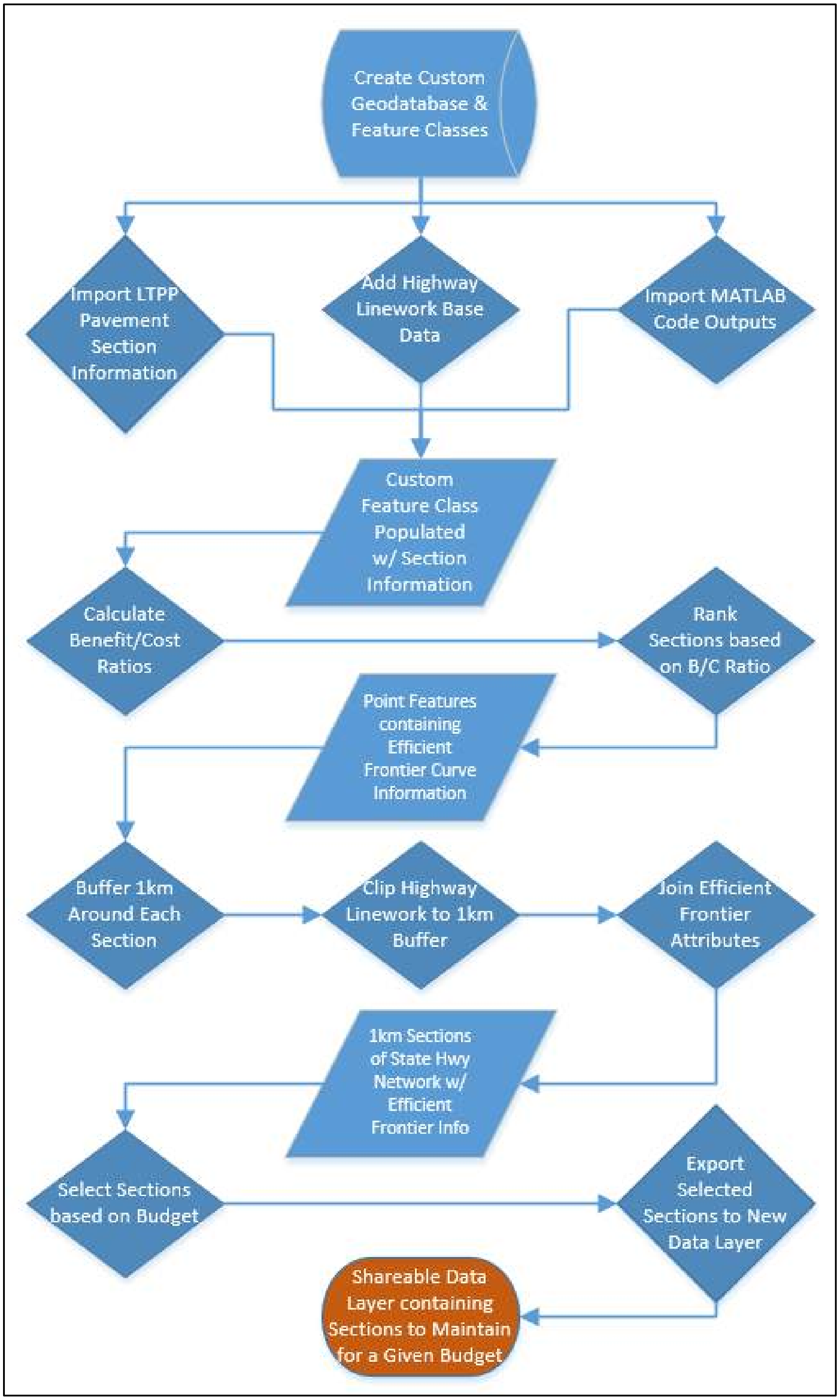

Figure 5.5. Flowchart for the GIS methodology

This section briefly overviews how GIS can be applied as an extension to the decision-making tool. It would add an element of spatial visualization to the decision-making tool results, making it easier for stakeholders to pinpoint where particular sections were and why they should be maintained. The creation of a shareable data layer with a small file size, including the sections to be maintained for a given budget, would allow for easy communication of road maintenance needs. Since state DOTs are beginning to increase their use of GIS for asset management, their organizations would be able to access the contents of this data layer easily. Furthermore, this data layer could be published to an online web map so that stakeholders could easily view it from a web browser, regardless of whether they had access to GIS software.

This GIS tool can also be applied to multiple trigger IRI scenarios. Using the custom tools created within the ArcGIS environment, a user could easily import MATLAB results for other trigger IRI values in order to produce a robust array of data layers encompassing multiple maintenance scenarios.

Chapter 6 Conclusions and Suggested Implementation Strategies

The goal of this study was to develop a network-level decision-making tool for efficient budget allocation for road maintenance and rehabilitation. Data associated with pavement structure, profile and traffic were obtained for 91 sections in Oregon, Idaho, Washington, and California. The IRI was considered to be the only pavement performance variable indicating pavement life and failure points. Two methods were used to estimate the failure points over a 40-year period for each section: 1) considering one value for trigger IRI for all the sections regardless of the traffic levels, and 2) considering different trigger IRIs for sections on the basis of their traffic levels (Madanat 2014). After the user benefits and agency costs were estimated, efficient frontier curves were developed for different trigger IRI values. The efficient frontier curves were compared with each other, and then the optimal trigger IRI for different budget levels, at which the user benefit was maximal, were obtained.

The results of this study showed that as the budget increases, the trigger IRI at which the user benefit is maximal decreases. This study also found that the method of considering one value for trigger IRI regardless of the traffic levels is more optimal for maximizing benefits than the Madanat (2014) method. It was also concluded that budget level controls the most optimal trigger IRI. Higher user benefits can be obtained by allocating a higher budget level to road maintenance (considering a lower value for trigger IRI).

Finally, to extend the utility of the network-level decision-making tool developed in this study, a prototype GIS map was created with ArcGIS. The goal was to create the ability for users to import LTPP road section data and the tool's MATLAB results into the GIS environment, spatially catalog this information, and then rank, highlight, and export selected roadway sections that present the highest benefit-to-cost ratios, or highest maintenance priority. To prove the methodology of the GIS process, 20 sections (5 sections in Oregon and 15 sections in Idaho) in the LTPP database were selected to spatially catalog. MATLAB outputs for a single trigger IRI of 170 inches/mile were selected arbitrarily as trial subjects. Then sections with higher priority to receive maintenance and rehabilitation for a given budget and trigger IRI value were located geographically. Spatial visualization of the decision-making tool results would help stakeholders in pinpointing where particular sections were and which sections should be maintained.

6.1 Future Study

On the basis of the conclusions from this research, the following recommendations are suggested:

- In this study, only IRI is used as a performance indicator. Structural number, wheel path cracking, and other performance variables from pavement management systems should be considered for characterizing pavement performance.
- Decision trees should be developed to choose the best treatment type at the end of the pavement life, rather than repeating the same treatment type over the analysis period.
- Reduction in energy consumption and GHG emissions should also be included in user benefits.
- The developed decision-making tool should be used to analyze the entire network for a state (all sections) using the automated pavement condition survey data.
- For this project, section coordinates were manually imported to GIS. A complete integration of MATLAB code with the GIS map system would be needed so that sections could be selected by MATLAB. Then sections' information should be sent to GIS to be automatically highlighted.

6.2. Suggested Implementation Strategies

After the recommendations suggested above have been followed, a finalized decision-making tool can be implemented. Two possible implementation strategies are as follows:

1. State DOTs can allocate budget to districts on the basis of pavement condition ratings. Each district will use the developed tool to identify the sections (or road segments) that will provide the highest level of user and agency benefits by considering user safety. The network for the analysis will be each district, not the whole state.
2. The tool can perform the budget allocation for an entire state DOT's highway network. DOTs can also incorporate their priorities (safety, structural integrity, minimum allowed pavement ratings, critical commercial areas, etc.) into the software to modify the tool's recommendations. The tool will estimate required budget for each district, and those amounts will be directed to every district. Then, each district will make its own prioritization to maintain the sections. Districts can consider the tool's recommendation in their decision process to maximize user benefits and safety.

Maps and tables showing the IRI trigger levels for different climate regions and traffic levels should also be developed. These maps and tables can be used by DOT pavement engineers and managers during the maintenance and rehabilitation decision-making process. Using the developed software, case studies should be developed to evaluate software decisions. A report and a presentation file will be prepared to document research findings and recommendations. It is expected that state DOT maintenance departments will implement the research findings to more effectively and efficiently manage roadway maintenance and rehabilitation.

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Appendix A
PAVEMENT HISTORY AND STRUCTURES FOR EACH SECTION

Section ID	Thickness (inches)	Section ID	Thickness (inches)	Section ID	Thickness (inches)
CA-0501-DGAC-CS	0.3	CA-8149-DGAC	1.9	ID-A320_DGAC_SS	0.2
CA-0502-DGAC-CS	0.2	CA-8150-DGAC	3.3	ID-A330_DGAC_CS	0.2
CA-0503-DGAC-CS	0.2	CA-8153-DGAC-CS	0.3	ID-A350_DGAC_CS	0.2
CA-0504-DGAC	5	CA-8156-DGAC-CS	0.1	ID-C320_DGAC_SS	0.2
CA-0505-DGAC-CS	0.2	CA-8201-DGAC-CS	0.2	ID-C330_DGAC_CS	0.6
CA-0506-DGAC	2.2	CA-8202-DGAC-CS	0.3	ID-C350_DGAC_CS	0.4
CA-0507-DGAC	4.6	CA-8534-OGAC	0.7	OR-2002_DGAC	2.3
CA-0508-RAPHL	4.3	CA-8535-DGAC-CS	0.1	OR-5006_CPR	2
CA-0509-RAPHL	2.1	CA-A310-DGAC	1.3	OR-5008_CPR	2
CA-0559-DGAC-CS	0.3	CA-A311-DGAC	1.4	OR-7018_CP	1.6
CA-0561-DGAC	1.9	CA-A320-DGAC-SS	0.3	OR-7019_CP	2.1
CA-0562-DGAC	2	CA-A321-DGAC-SS	0.2	WA-1005_DGAC	2.1
CA-0563-DGAC	2.2	CA-A330-DGAC-CS	0.2	WA-1006_DGAC_CS	0.1
CA-0565-DGAC	2.7	CA-A340-DGAC-CS	0.2	WA-1007_DGAC	2.3
CA-0566-OGAC	0.6	CA-A350-DGAC-CS	0.3	WA-1008_DGAC	1.7
CA-0567-OGAC	0.8	CA-A351-DGAC-CS	0.2	WA-1501_DGAC	1.9
CA-0568-DGAC	4.4	CA-A352-DGAC-CS	0.4	WA-1801_DGAC	4.5
CA-0569-DGAC	1.7	CA-A353-DGAC-CS	0.3	WA-6020_DGAC	2.7
CA-0570-DGAC-CS	0.4	CA-A361-DGAC	2	WA-6048_RAPHL	2.8
CA-0571-RAPHL	1.8	CA-A362-DGAC	1	WA-6056_RAPCL	1.8
CA-1253-DGAC-CS	0.2	CA-A363-DGAC-CS	0.2	WA-7322_DGAC	1.8
CA-2002-DGAC	3.5	ID-1001_DGAC	1.2	WA-A320-DGAC-SS	0.2
CA-2004-OGAC	0.7	ID-1005_DGAC_CS	0.4	WA-A350-DGAC-SS	0.2
CA-2038-DGAC-CS	0.2	ID-1007_DGAC_CS	0.2	WA-B310-DGAC	1.3
CA-2041-DGAC	3.4	ID-1009_DGAC_CSMB	0.6	WA-B320-DGAC-SS	0.2
CA-2051-DGAC	0.1	ID-1010_DGAC_CS	0.2	WA-B330-DGAC	2
CA-2053-DGAC	4.1	ID-1020_DGAC_CS	0.2	WA-B350-DGAC-CS	0.5
CA-2647-DGAC-CS	0.1	ID-9032_DGAC_CS	0.4	WA-C310-DGAC	1.1
CA-6044-DGAC	4.8	ID-9034_DGAC	2	WA-C320-DGAC-SS	0.2
CA-7452-DGAC	1.4	ID-A310_DGAC	1	WA-C350-DGAC-CS	0.3
CA-7491-DGAC	4				

DGAC: dense graded asphalt concrete.
DGAC_CS: chip-seal on dense graded asphalt concrete overlaid.
DGAC_SS: slurry-seal on dense graded asphalt concrete overlaid.
DGAC_CSMB: chip-seal with modified binder on dense graded asphalt concrete overlaid.
CP: composite pavement.
CPR: composite pavement having RAP.
RAPCL: cold-laid recycled asphalt pavement.
RAPHL: hot-laid recycled asphalt pavement.