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Integration of Pavement Cracking Prediction Model with Asset Management and Vehicle-Infrastructure Interaction Models

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DISCLAIMER

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CHAPTER 1. INTRODUCTION

1.1 Background and motivation

Not long after the construction of a pavement or a new pavement surface, various forms of deterioration begin to accumulate due to the harsh effects of traffic loading combined with weathering action. In a recent NEXTRANS project, a pavement cracking prediction tool is developed, which can predict fundamental material fracture response and is capable of performing thermal cracking simulations. This deteriorated pavement condition, which is the sum effect of a number of distinct deterioration modes or ‘distresses,’ increases not only agency costs but also user costs. It is required to consider both users and agency investments while making decision for pavement maintenance and rehabilitation for better financial management. The material selection process can be optimized by incorporating user costs via pavement life-cycle analysis and maintaining pavement distress levels using the pavement cracking prediction tool. Pavement condition has significant impacts on user costs. There are many indices that represent pavement condition. International Roughness Index (IRI) is widely used to quantify pavement smoothness. From the driving comfort viewpoint, smoothness is considered as the most important aspect of pavement condition, and it is especially important for pavements with elevated speed limits. Highway agencies generally have their own specifications of IRI level for different classes of roadways. Roughness increases user costs including fuel, repair and maintenance, depreciation, and tire costs. User costs across a vehicle fleet resulting from increased roughness is undoubtedly significant, but has not been well quantified in light of newly available prediction tools.

1.2 Problem statement

Very little research has been undertaken to integrate fundamental predictions of pavement deterioration with pavement roughness and its effect on vehicles maintenance and driver safety. In a current NEXTRANS project, a pavement cracking prediction tool is developed, which can predict fundamental material fracture response utilizing a cohesive zone model within a finite element framework. A newly developed graphical user interface (GUI) for the simulation software has been demonstrated at a recent NEXTRANS summit. This tool is capable of performing thermal cracking simulations and is expected to be widely utilized by State Department of Transportation (DOT) engineers as well as other transportation agency engineers (county, city, federal etc.) for the design of asphalt pavements and overlays that are resistant against thermally induced cracking. Integration with more general asset management system is currently underway.

1.3 Study objectives

The main objective of this study is to develop an integrated framework that allows for linking of pavement simulation software (such as, pavement cracking prediction software developed under a previous NEXTRANS project) with actual pavement cracking, distress and roughness, and to develop a framework that links the pavement roughness and distress information with vehicle maintenance and driver comfort.

The objectives of this study are to: (1) prediction of pavement distress such as low temperature cracking, (2) estimate different types of user costs incurred by pavement roughness resulting from distresses, (3) compare agency investments for different maintenance and rehabilitation strategies and associated roughness-related user costs, (4) analyze environmental impacts of construction, maintenance, and rehabilitation (CMR) activities used in pavement engineering, (5) estimate and compare agency costs, user costs due to roughness, and emission costs due to CMR activities, and; (6) estimate emission costs associated with pavement roughness. By considering the cost associated with the environmental impact of CMR activities, a more realistic estimate of the ROI associated with maintaining relatively smooth pavement throughout its service life was assessed.

This presents a holistic approach to pavement design and maintenance, with the ultimate goal of providing the USDOT with a tool to decrease life cycle costs of a pavement system in a much broader sense, and moreover, to enhance safety through scientifically informed design and maintenance decisions.

1.4 Organization of the research

This study is mainly focused on pavement cracking prediction, resulting driving discomfort which is measured by roughness, incurred users costs, and recommendations to adjust initial pavement design and maintenance and rehabilitations activities. The entire process is illustrated in Figure 1.

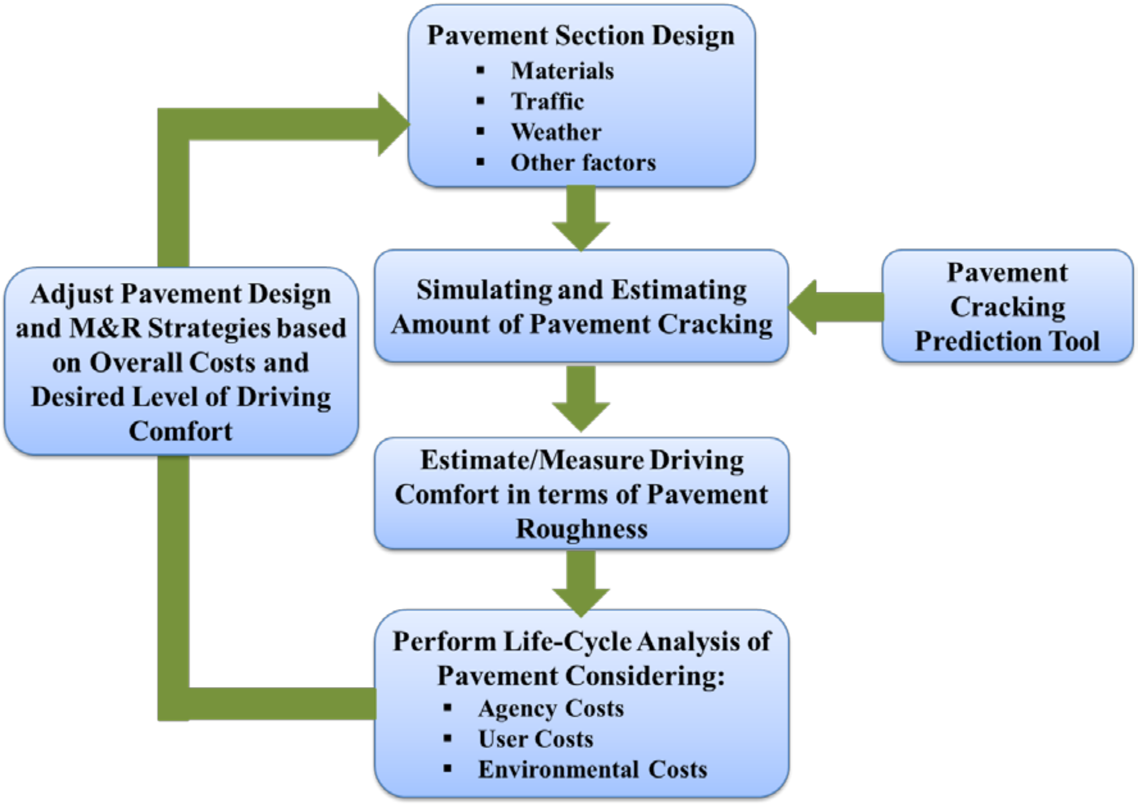

Figure 1.1 An approach to make pavement design and maintenance decision

Chapter two discusses pavement cracking prediction using M-E PDG software program where different levels of analysis were performed with different asphalt binder. It also discusses agency costs such as initial construction, maintenance, and rehabilitations costs for 35 years of pavement life. As pavement roughness increases user costs such as fuel, tire, depreciation, and maintenance costs, models to estimate these parameters are also discussed in Chapter two.

Chapter three includes pavement cracking prediction with different kinds of asphalt binder. It also discusses estimation pavement roughness because of pavement cracking.

Chapter four discusses user costs associated with four alternative maintenance and rehabilitation activities over 35 years of pavement design life. It includes estimation of fuel costs, tire costs, depreciation costs, and repair costs. It also discusses environmental impacts of maintenance and rehabilitation activities in conjunction to reduce pavement roughness.

Chapter five discusses overall agency, users, and environmental costs associates with pavements. It also summarizes motorists extra vehicle repair and maintenance costs across the US as a result of poor pavement condition.

Chapter six summarizes the project work and findings. It also provides recommendations to further extend this study.

CHAPTER 2. PAVEMENT DISTRESS AND RELATED COSTS

2.1 <u>Introduction</u>

Pavement cracking prediction ahead of pavement construction is an important input for a comprehensive pavement management system. This kind of prediction can help to modify pavement materials selection, effective planning of maintenance and rehabilitation activities, and investment decisions. Although agency costs for a given pavement facility are very significant at the time of initial construction and when major rehabilitation activities performed, pavement user costs may also be significant when the total fleet using those facilities is considered. Pavement agency costs include initial construction, maintenance, rehabilitation, and engineering administration. Pavement user costs include fuel, oil, tire repair and replacement, vehicle maintenance and repair, depreciation, travel time delay, and driver discomfort/injury.

2.2 <u>Pavement cracking prediction using MEPDG</u>

In a recent NexTrans project, a pavement cracking prediction tool has been developed. In this study, pavement cracking prediction of MEPDG software program has been evaluated. In particular, the predicted amounts of thermal cracking were examined. For the first portion of the research program, the goal was to find which asphalt binders reach the threshold of thermal cracking within one winter in a given climate. The threshold of thermal cracking was set as 200 feet of transverse cracking per 500 feet of pavement. Several different climates were examined, each with a different length and severity of winter season. After examining the predicted amount of thermal cracking, appropriate asphalt binders could be selected for use in new pavement structures.

“Softer” binders, which are graded for better performance in low temperatures, would be expected to crack less under thermal stresses.

2.3 *Pavement agency costs*

Various DOT’s have their own unique pavement rehabilitation and maintenance (R&M) strategies. In this study, four alternative strategies have been considered. Cost information for different rehabilitation and maintenance techniques was collected from DOT’s as retrieved from the literature. As these data were collected from different sources, data was inflated using the relevant Consumer Price Index (CPI) and expressed in 2011 dollars. According to FHWA (2011), “the Consumer Price Index (CPI) measures the changes in the cost of purchasing products and services”. FHWA also maintains a similar cost index for highway construction activities. According to FHWA (2011), the Federal-aid highway Construction Index (CI) is computed based on the unit costs of excavation, resurfacing, and construction, and reflects cost changes for materials such as reinforcing steel, bituminous concrete, Portland cement and other ingredients for highway projects across the country. As CI is not available for most recent years, CPI was used in this study.

2.4 *Pavement user costs*

2.4.1 **Fuel cost**

Fuel is an important component of pavement user costs, and has been reported to account for as much as 50-75% of total pavement user costs (Sinha and Labi 2007). Fuel consumption depends on vehicle class, and factors that affect fuel consumption include vehicle type, class, age, vehicle technology, pavement surface type, pavement condition, speed, roadway geometry, environment, etc. According to the American Automobile Association (2011), the composite national average driving cost per-mile for 2010 was 58.5 cents, based on $2.88 per gallon fuel cost. Fuel consumption is directly related to forces acting on the vehicle, including aerodynamic, rolling resistance, gradient, curvature, and inertial forces. Zaniewski (1989) reported that fuel consumption of automobiles is not dependent on pavement surface type. Lu (1985) reported that pavement rolling resistance depends on pavement roughness, and that an IRI reduction of 129 inch/mile will result in a 10% drop in rolling resistance. A decrease in rolling resistance by 10% increases fuel economy by 1% to 2%, according to TRB Special Report 286. This increase in fuel economy would save about 1.75 to 3.5 billion gallons of fuel per year of the 175.2 billion gallon consumed by the total highway fleet in the year 2008 (FHWA 2011), if this improvement in rolling resistance could be attained. Thus, maintaining pavement surface smoothness could potentially save billions of dollars annually in the US.

There are many models available to estimate vehicular fuel consumption, which are often termed as vehicle operating cost (VOC) models. The models include: (a) Texas Research and Development Foundation (TRDF) model; (b) World Bank's HDM-4 model; (c) Saskatchewan models; (d) ARFCOM: Australian Road Fuel Consumption model; (e) New Zealand VOC model; (f) South African VOC models, and; (g) Swedish mechanistic model for simulations on road traffic (VETO). HDM-4, the most recent VOC model, clearly shows that pavement roughness affects fuel consumption. As the HDM-4 model was developed based upon data from developing countries, Zaabar and Chatti (2010) calibrated the model to consider US conditions. They estimated the increase in fuel consumption based on pavement roughness for different types of vehicles, which was converted into equation form for the purposes of this study:

$$\textit{\% Increase in Fuel Consumption} = \mathbf{0.0157} \times \boldsymbol{IRI} - \mathbf{0.996} \cdots \cdots (\mathbf{1})$$

Here, IRI is pavement roughness expressed in units of inches/mile. This above equation was used to estimate increase in pavement user costs, as described later in this paper.

The Environmental Protection Agency (EPA) estimates annual fuel costs for different types of vehicle. For this study, arbitrarily, a mid-sized Honda Accord M-6 car was selected. According to EPA (2010), fuel cost for this car is 15.12 cents/mile considering 15000 miles driven per year (55% city, 45% highway) and a fuel price of $3.78/gal.

2.4.2 **Repair and maintenance costs**

Repair and maintenance includes user costs (parts and labor) required because of vehicular wear and tear. Zaniewski et al. (1982) developed the only model found in the literature based on US conditions. The World Bank's recent HDM-4 model is based on data from developing countries (Bennett and Greenwood 2003); however, Zaabar and Chatti (2010) reported repair and maintenance cost predictions by the HDM-4 model is reasonable for US conditions. According to HDM-4, the effect of pavement roughness on repair and maintenance cost is negligible at low (193 inch/mile) IRI. However, Zaniewski et al. (1982) modified a World Bank study which was based on data from Brazil to investigate the effect of roughness on repair and maintenance costs and proposed adjustment factors based on the present serviceability index (PSI) parameter, which provides a numeric rating of current pavement condition. According to the authors, the multiplying factor for repair and maintenance cost would be 1.00 at a PSI value of 3.5. Later PSI values were converted to IRI (Table 2.1) using a transfer equation generated by Hall and Correa (1999).

Table 2.1 Multiplying factors (MF) for repair and maintenance costs generated from Zaniewski et al. (1982)

PSI	(IRI), inch/mile	MF for Passenger Car and Pickup Trucks	Vehicle Class	Average Cost, $/1000-mile		
				Zaniewski et al. (1982)	2007 Value, Zaabar and Chatti (2010)	2011 Cost
4.5	40	0.83	Small Car	34.50	64.73	69.77
4.0	63	0.90	Medium Car	41.84		
3.5	84	1.00	Large Car	48.33		
3.0	123	1.15	Pick Up	53.12	83.31	89.81
2.5	180	1.37	Light Truck	99.59	148.24	159.80
2.0	320	1.71	Medium Truck	140.82	190.83	205.71
1.5	610	1.98	Heavy Truck	140.82	191.95	206.92

The following equation was fitted to find a relationship between IRI and repair and maintenance (R&M) cost.

$$\textbf{\textit{Multiplying Factor (MF) for R\&M}} = -5 \times 10^{-6} \times IRI^{2} + 0.0049 \times IRI + 0.6239 \cdots \cdots (2)$$

$R^2 = 0.9986$

Where, IRI is in inch/mile

Zaniewski et al. (1982) proposed repair and maintenance costs for different types of vehicles and Zaabar and Chatti (2010) updated this cost to 2007 dollar value. In this study, cost information was updated to 2011 dollar value to estimate additional user costs incurred as a result of pavement roughness.

2.4.3 **Depreciation costs**

Chesher et al. (1981) reported, from a study performed based on developing countries data, that vehicular depreciation rate is dependent on pavement roughness. Studies performed in developed countries have also shown that roughness affects depreciation costs. Vehicle depreciation cost depends on mileage driven and age of vehicle. According to Haugodegard et al. (1994), a major part (70%) of depreciation cost depends on vehicle age and a minor part (30%) on mileage. They also observed that mileage-related depreciation depends on pavement roughness. Zaniewski et al. (1982) studied depreciation cost based on a survey and vehicle registration data. They proposed adjustment factors based on a PSI of 3.5. Table 2.2 represents multiplying factor for depreciation cost.

Table 2.2 Multiplying factor for depreciation cost based IRI and Zaniewski et al. (1982)

Present Serviceability Index (PSI)	International Roughness Index (IRI), inch/mile	MF for Passenger Car and Pickup Trucks
4.5	40	0.98
4.0	63	0.99
3.5	84	1.00
3.0	123	1.02
2.5	180	1.04
2.0	320	1.06
1.5	610	1.09

The following equation was developed using data reported in Table 3 to establish a formulaic relationship between IRI and depreciation cost.

Multiplying Factor (MF) for Depreciation $\boldsymbol{= -1 \times 10^{-6} \times IRI^{2} + 0.0007 \times IRI + 0.9535 \cdots \cdots (3)}$

$R^2 = 0.9983$

where, IRI is in units of inches/mile. This equation was used in this study to estimate depreciation cost at different levels of IRI.

FHWA (2002) reported average vehicle depreciation cost of different types vehicles. This study found that mileage related depreciation costs for a medium or large sized auto is 9.8 cents/mile in 1995 dollars. According to Barnes and Langworthy (2004), a baseline depreciation cost of an automobile in highway and smooth pavement condition is 6.2 cents/mile in 2003 dollars. Applying the CPI, this depreciation cost would be 7.53 cents/mile in 2011 dollars, which has been subsequently used in this paper to estimate additional cost incurred by pavement roughness.

2.4.4 **Tire costs**

Zaniewski et al. (1982) developed an adjustment factor to estimate tire cost as a function of pavement condition, using a PSI of 3.5 as reference, where tire cost increases with pavement roughness (Papagiannakis and Delwar 1999). The effect of distance traveled and tire load are greater than that of pavement roughness on tire wear (Papagiannakis and Delwar 1999). Tire wear depends on roughness, and highly abrasive aggregate has an effect on tire wear (Papagiannakis and Delwar 1999). Haugodegard et al (1994) showed, based on a Norwegian study, a definite increasing trend of tire wear with pavement roughness. Table 2.3 presents multiplying factors for tire cost.

Table 2.3 Multiplying factor for tire cost based on IRI and Zaniewski et al. (1982)

Present Serviceability Index (PSI)	International Roughness Index (IRI), inch/mile	MF for Passenger Car and Pickup Trucks
4.5	40	0.76
4.0	63	0.86
3.5	84	1.00
3.0	123	1.16
2.5	180	1.37
2.0	320	1.64
1.5	610	1.97

The following equation was fitted from Table 4 to find a relationship between IRI and tire cost.

$$\textbf{\textit{Multiplying Factor (MF) for Tire Cost}} = \boldsymbol{-9 \times 10^{-6} \times IRI^{2} + 0.0064 \times IRI + 0.5133 \cdots \cdots (4)}$$

$R^2 = 0.9989$

Where, IRI is in inch/mile. This equation was used in this study to estimate tire cost at different levels of IRI.

According to Barnes and Langworthy (2003), baseline tire cost for an automobile operated on a highway with a smooth pavement condition is 0.9 cents/mile in 2003 dollars. By using CPI, this tire cost is 1.1 cents/mile in 2011 dollar which has been later used to estimate additional cost incurred due to pavement roughness.

CHAPTER 3. PAVEMENT DISTRESS AND DRIVING CONFORT PREDICTION

3.1 Introduction

Pavement cracking and other distresses are the main attributes which affect driving comforts. In this study, pavement cracking was predicted with help of MEPDG program for different asphalt binders, and resulting pavement roughness was also estimated.

3.2 Pavement cracking prediction

The MEPDG program produces monthly data for pavement distresses. From this data, the amount of thermal cracking at several different years (typically 1, 5, 10, 15, and 20) was recorded for analysis in this project. If the pavement reached the maximum level of cracking before the end of the design life, the time to failure was recorded. The thermal cracking data was recorded for each asphalt binder in each of the three climates tested. A sample of the data results is shown below in Tables 3.1 and 3.2. The minimum time any asphalt binder took to reach the maximum thermal cracking was approximately 3 months, or within the first winter of the theoretical construction of the pavement.

Table 3.1 Comparison of MEPDG pavement cracking prediction of Level 3 and Level 1

Level 3 Analysis					
Climate	**Binder**	**Cracking @ 5 Years**	**Cracking @ 10 Years**	**Cracking @ 15 Years**	**Cracking @ 20 Years**
Intermediate	PG 64-22	0.245	4.077	12.572	23.917
	PG 70-22	0.072	1.212	3.735	7.290
	PG 76-22	0.019	0.337	1.022	1.972
	PG 64-28	0.002	0.028	0.079	0.149
	PG 70-28	0.000	0.009	0.026	0.050
	PG 76-28	0.000	0.004	0.013	0.024

Level 1 Analysis					
Climate	**Binder**	**Cracking @ 5 Years**	**Cracking @ 10 Years**	**Cracking @ 15 Years**	**Cracking @ 20 Years**
Intermediate	PG 64-22	38.199	145.688	172.767	177.920
	PG 70-22	Max cracking: 200 @ 15.3 mo.		-	
	PG 76-22	-	-	-	-
	PG 64-28	0.000	0.001	0.002	0.004
	PG 70-28	-	-	-	-
	PG 76-28	-	-	-	-

Note 1: IDT data not available for PG 76-22, PG 70-28, and PG 76-28 asphalt binders

Note 2: Cracking shown in terms of feet per 500 feet (200 ft. maximum)
Pavement Structure: 5” HMA, 8” crushed stone base, A-7-6 subgrade

Table 3.2 MEPDG Level 1 pavement cracking prediction analysis results

Cold Climate (International Falls, MN)				
Binder	**Cracking @ 5 Years**	**Cracking@10 Years**	**Cracking@15 Years**	**Cracking@20 Years**
PG 64-22	157.8	177.0	180.1	182.8
PG 70-22	Maxed out: 200 @ 3.4 mo.			
PG 64-28	0.04	2.5	9.2	22.9
Intermediate Climate (Champaign, IL)				
Binder	**Cracking @ 5 Years**	**Cracking @10 Years**	**Cracking @15 Years**	**Cracking @20 Years**
PG 64-22	11.067	67.022	83.291	87.552
PG 70-22	Maxed out: 200 @ 15.3 mo.			
PG 64-28	0.000	0.001	0.002	0.004
Warm Climate (Flagstaff, AZ)				
Binder	**Cracking @ 5 Years**	**Cracking @ 10 Years**	**Cracking @15 Years**	**Cracking @20 Years**
PG 64-22	0.004	0.04	0.2	0.4
PG 70-22	72.2	92.2	96.7	102.5
PG 64-28	0.0	0.0	0.0	0.0

With the University of Illinois IDT data, the weakest binder, in regards to thermal cracking, was seen to be PG 70-22, regardless of climate. The most effective binder against thermal cracking was seen to be PG 64-28. However, it must be noted that the Level 1 analysis was performed using the data from just a single IDT. Additional IDT results were not available for the PG 64-28 binder during this study.

The trends of thermal cracking for the various binders were consistent across the three climates. The only difference among the climates was the degree of thermal cracking that occurred. For the sake of space in this report, only the results from the full depth pavement set are shown in Table 3.2. Sets 2, 3, and 4 yielded similar trends in thermal cracking. As the thickness of the asphalt concrete layer decreased, the amount of thermal cracking increased uniformly, regardless of climate. As expected, thermal cracking was greatest in the cold climate of International Falls, MN, and least in the warm climate of Flagstaff, AZ. However, the binders showed similar trends in thermal cracking relative to other binders. The weakest binder always experienced the most thermal cracking, while the most effective binder showed the least thermal cracking, or no thermal cracking at all.

With the MEPDG default data, the most cracking susceptible binder was found to be PG 70-16. The most effective binder for thermal cracking was PG 46-40. The IDT database did not have data for those binders, as they are not typically used in the State of Illinois. The asphalt binder grades chosen for Level 3 analysis were chosen to show sequential differences in maximum and minimum design temperature from PG 64-22, the typical binder used in Illinois. One of the unexpected results of the level 3 analysis was that the PG 70-16 binder consistently performed worse than the PG 76-10 binder. The PG 76-10 binder should have experienced the most predicted thermal cracking, since it had the highest minimum temperature grade. However, these are seldom used grades.

As part of this research project, the differences in results between pavements with the default MEPDG data and the IDT data from the University of Illinois were examined. The discrepancies between the Level 1 and Level 3 analyses conducted with the MEPDG are shown in Table 3.1 below. For PG 64-22, over a design life of 20 years, 87.6 feet of transverse cracking per 500 feet of pavement was predicted to occur by MEPDG using IDT data (Level 1 analysis). Using the default MEPDG data, only 23.9 feet of transverse cracking per 500 feet of pavement was predicted (Level 3 analysis). The results of the MEPDG testing with the IDT creep compliance and tensile strength data showed a consistently higher level of thermal cracking. Overall, the results of this research show that the default creep compliance and tensile strength data for the asphalt binders in the MEPDG may need to be updated in order to achieve more reasonable results.

The calibration factors used for thermal cracking were adjusted so that MEPDG predictions would match an expert’s predictions. For the level 3 analysis in Champaign, IL, the ideal calibration factor was found to be 1.73. For the level 1 analysis in Champaign, IL, the ideal calibration factor was found to be approximately 0.97. The difference in these regional calibration factors further demonstrates the disparity between the level 1 and level 3 analysis results.

3.3 Pavement roughness prediction example

Pavements begin deteriorating after construction due to traffic loads and environmental factors. Pavement surface roughness increases with the extent and severity of various distresses, which affects ride quality, safety, travel speed, and vehicle operating costs. There are many pavement roughness models which were developed using different distresses for new and overlaid pavements (Von Quintus et al. 2001). In this study, the IRI model that appears on the M-E PDG (AASHTO 2008) was used to predict pavement roughness:

$$IRI = IRI_0 + 0.0150*SF + 0.400*FC_{Total} + 0.0080*TC + 40*RD$$

Where, IRI_0 = Initial IRI, inch/mile

SF = Site Factor

FC_{Total} = Area of fatigue cracking (combined alligator, longitudinal, and reflection cracking under the wheel path), in percentage of total lane area

TC = Length of transverse cracking in feet per mile

RD = Average rut depth measured in inches

The following inputs were used for MEPDG analysis of 12-inch full depth asphalt pavement, along with program default values:

AADT = 10000

Asphalt Binder = PG 64-22

Asphalt creep and strength data: University of Illinois, Buttlar group database

Initial IRI = 63 inch/mile and 70 inch/mile

Climate: Champaign, IL

Design life: 20 years

Table 3.3 shows the predicted IRI of a 12-inch, full-depth asphalt pavement.

Table 3.3 Prediction of IRI using M-E PDG software program

Year	Transverse Cracking (ft./mi)	IRI (When Initial IRI = 63 inch/mile)	IRI (When Initial IRI = 70 inch/mile)
1	0	76.3	83.3
2	12.3	80.1	87.1
3	39.8	83	90
4	111	86.6	93.6
5	117	89.6	96.6
6	315	93.5	100.5
7	599	98.5	105.5
8	604	101.4	108.4
9	606	104.3	111.3
10	708	108.3	115.3
11	729	111.2	118.2
12	756	114.6	121.6
13	757	117.8	124.8
14	798	121.2	128.2
15	880	124.9	131.9
16	881	128.3	135.3
17	882	131.6	138.6
18	908	135.4	142.4
19	915	138.8	145.8
20	925	142.5	149.5

Perera and Kohn (2006) reported that, for pavement sections with IRI greater than 97 inch/mile before applying an overlay, the IRI after placing the overlay was reduced to between 52 to 76 inch/mile. They also reported that IRI values would be less than 64 inch/mile after the application of an overlay when pre-overlay IRI values of less than 97 inch/mile were present. Thus, for roughness prediction of pavement following rehabilitation, an IRI level of (63 inch/mile) was assumed in this study. Maintenance represents pavement improvement activities which are performed when pavement is in a structurally sound, good condition. Al-Mansour et al. (1994) studied the effect of crack sealing, chip seal, and sand seal on roughness in flexible pavements used on interstate and state highways. They reported low benefits in roughness reduction due to maintenance activities in the case of new pavements and increased benefit in roughness reduction for maintenance applied to aged pavements. Hall et al. (2002) studied the effect of various maintenance activates, including slurry seal, chip seal, crack seal, and thin overlays on pavement roughness. Based upon a statistical analysis, they reported that the effect of chip seals, crack seals, and slurry seals were not significant compared to a control section which did not receive a maintenance treatment. However, thin overlays were found to reduce pavement roughness significantly. In this study, no improvement in IRI was considered for pavements undergoing chip seals, slurry seals, and crack seals, while a roughness reduction resulting in a restored IRI level of 63 inch/mile was assumed following the application of an overlay. Although rate of change of IRI for overlays is higher than new pavement IRI deterioration, the same rate was considered for simplicity of calculation in this study.

CHAPTER 4. ESTIMATION OF COSTS DUE TO PAVEMENT ROUGHNESS

Chapter 4 presents an analysis of user costs resulting from pavement roughness. In Chapter two and Chapter three, pavement cracking prediction along with resulting roughness and methods of user costs estimation were presented. In this section, total user cost per 1-mile pavement section has been estimated for an assumed vehicle fleet.

4.1 Pavement user costs with conventional M&R

Different types of pavement user costs were estimated by using the equations and user cost data provided in the above sections. Table 4.1 shows increases in user costs i.e. fuel consumption, repair and maintenance, depreciation, and tire cost, at different levels of IRI as predicted by the AASHTO Mechanistic Empirical Pavement Design Guide (MEPDG) software program. Total roughness-related user costs are also shown in Table 4.1 for a fleet of 10,000 vehicles, assumed to travel an average of 12,000 miles per year. From Table 4.1, it can be seen that a vehicle owner will incur an additional $129/year for a vehicle driven on road with an IRI of 110 inch/mile, which is considered to be an adequate smoothness level for a primary road. This additional user cost would be higher ($478/year) if the same vehicle were driven on road with an IRI of 200 inch/mile, which is the highest acceptable IRI level for a primary road.

Table 4.1 Total user cost increased due to pavement roughness

IRI, inch/mile	Increase in Fuel Cost, $/mile from Eq. (1)	Increase in R&M Cost by Eq. (2), $/mile	Increase in Depreciation Cost by Eq.(3), $/mile	Increase in Tire Cost by Eq. (4), $/mile	Total Increase in User Cost, $/mile	Total Cost per Year for 10,000 vehicle, $	Total Cost 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
108.3	0.00106	0.006625	0.00132	0.00110	0.01011	$1,212,824	$121
100[1]	0.00087	0.004413	0.00101	0.00069	0.00698	$837,947	$84
110[2]	0.00111	0.007072	0.00138	0.00118	0.01074	$1,288,548	$129
125[3]	0.00146	0.010931	0.00190	0.00188	0.01618	$1,941,125	$194
175[4]	0.00265	0.022673	0.00340	0.00390	0.03262	$3,914,234	$391
200[5]	0.00324	0.027896	0.00401	0.00472	0.03987	$4,784,164	$478
250[6]	0.00443	0.037047	0.00495	0.00600	0.05242	$6,290,776	$629

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[1] IRI level for adequate smooth pavement of Interstate highways
[2] IRI level for adequate smooth pavement of Primary roads
[3] IRI level for adequate smooth pavement of Secondary roads
[4] IRI level for inadequate smooth pavement of Interstate highways
[5] IRI level for inadequate smooth pavement of Primary roads
[6] IRI level for inadequate smooth pavement of Secondary roads

Agency costs for four different maintenance and rehabilitation (M&R) strategies were estimated. The effects of M&R activities on pavement roughness were estimated from data found through literature review (Hall et al. 2002). Table 4.2 shows agency costs for four alternative M&R strategies. To calculate life-cycle cost of pavement, a 35 year analysis period and a 3% discount rate was considered. A comparison was then made between agency costs and costs related to pavement roughness, as shown in Figure 4.1.

Table 4.2 Pavement maintenance and rehabilitation (M&R) strategies (1-mile)

Alternative 1			**Alternative 2**		
Year	Action	Cost	Year	Action	Cost
0	New Pavement	$206,712	0	New Pavement	$206,712
3	Crack Seal (4 yrs)	$1,500	3	Crack Seal (4 yrs)	$1,500
7	Crack Seal (4 yrs)	$1,500	7	Mill & Patch 20% Spot Repair	$18,050
10	2" Overlay (10 yrs)	$92,810	15	2" Mill & 2" Overlay	$94,090
13	Crack Seal (4 yrs)	$1,500	18	Crack Seal (4 yrs)	$1,500
16	Slurry Seal (4 yrs)	$11,265	20	Mill & Patch 20% Spot Repair	$18,050
20	2" Mill & 2" Overlay	$94,090	27	1.5" Mill & 3" Overlay	$110,860
23	Crack Seal (4 yrs)	$1,500	30	Crack Seal (4 yrs)	$1,500
26	Chip Seal (5 yrs)	$12,530	35	Salvage Value	-$33,258
30	2" Mill & 2" Overlay	$94,090			
35	Salvage Value	-$47,045			
	Present Worth =	$367,115		Present Worth =	$332,735
	EUAC =	$ 17,085		EUAC =	$ 15,485
Alternative 3			**Alternative 4**		
Year	Action	Cost	Year	Action	Cost
0	New Pavement	$206,712	0	New Pavement	$206,712
3	Crack Seal (4 yrs)	$1,500	3	Crack Seal (4 yrs)	$1,500
5	Chip Seal (5 yrs)	$12,530	5	Crack Seal (4 yrs)	$1,500
10	1.5" Overlay (10 yrs)	$77,585	9	Mill & Patch 20% Spot Repair	$18,050
14	Crack Seal (4 yrs)	$1,500	12	Chip Seal (5 yrs)	$12,530
17	Slurry Seal (4 yrs)	$11,265	17	2" Mill & 2" Overlay	$94,090
20	2" Mill & 2" Overlay	$94,090	20	Crack Seal (4 yrs)	$1,500
23	Crack Seal (4 yrs)	$1,500	23	Slurry Seal (4 yrs)	$11,265
26	Fog Seal (2 yrs)	$9,700	27	1.5" Overlay (10 yrs)	$77,585
30	1.5" Overlay (10 yrs)	$77,585	30	Crack Seal (4 yrs)	$1,500
35	Salvage Value	-$38,792	35	Salvage Value	-$15,517
	Present Worth =	$359,962		Present Worth =	$325,497
	EUAC =	$ 16,752		EUAC =	$ 15,148

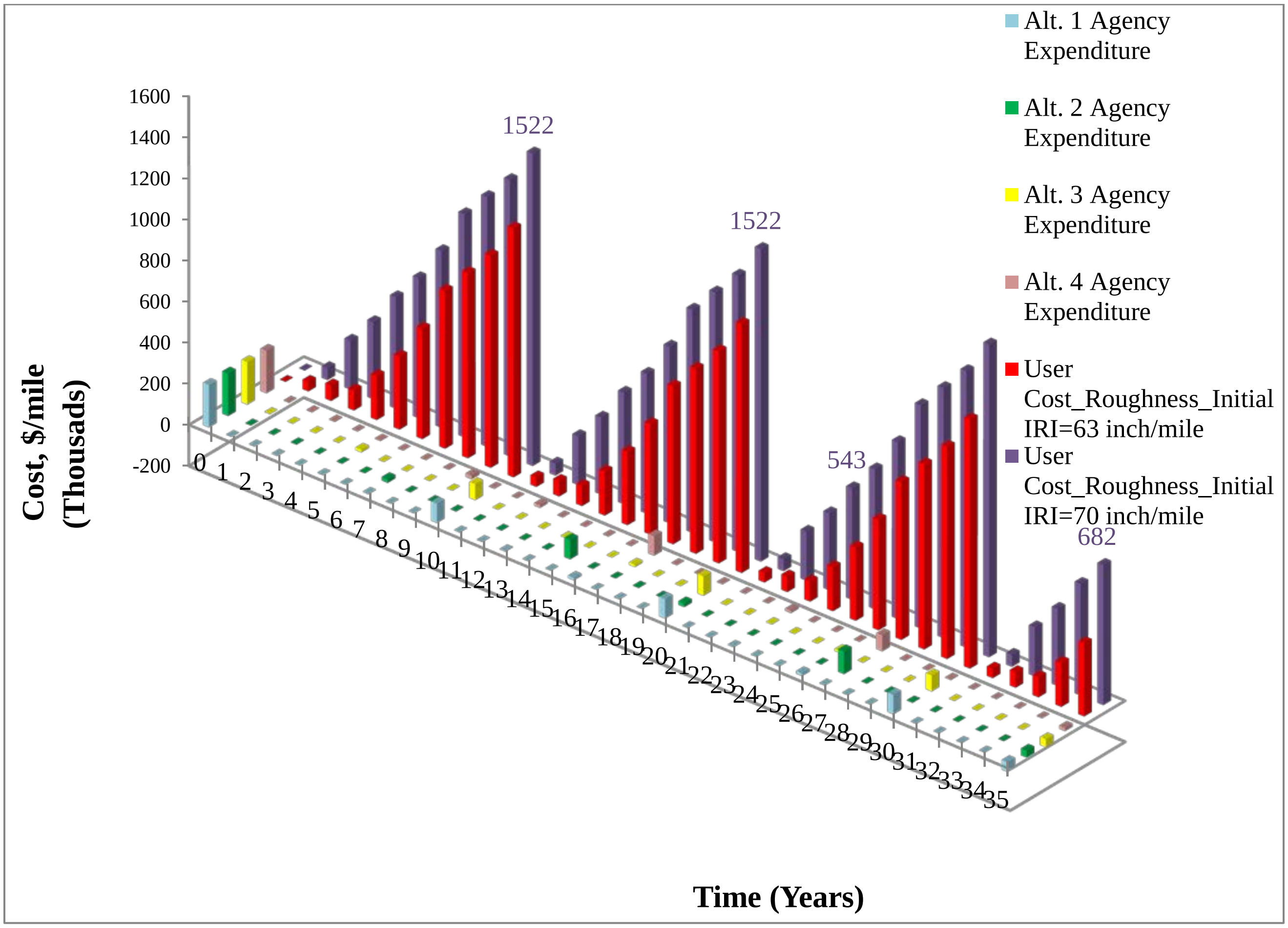

Figure 4.1 Comparison between agency costs and user costs related to pavement roughness

In Figure 4.1, roughness cost was calculated assuming 12,000 mile/year and a 10,000 annual average daily traffic (AADT) level. It can be seen that the present worth (PW) of the pavement from the LCCA was found to be about $350,000, whereas cost related to roughness was about $9,910,000 to $15,460,000 depending on the initial roughness of the pavement. This finding suggests that highway agencies only expend about 2.3% to 3.6% of the amount that is spent by users ***as a result of pavement roughness*** over the period of the LCC.

In this study, agency costs and costs incurred because of pavement roughness were considered, not total vehicle operating cost. Figures 4.2 and 4.3 show that vehicle maintenance and repair costs increase significantly with IRI, amounting to about 56% to 60% of the total costs considered, depending upon initial IRI.

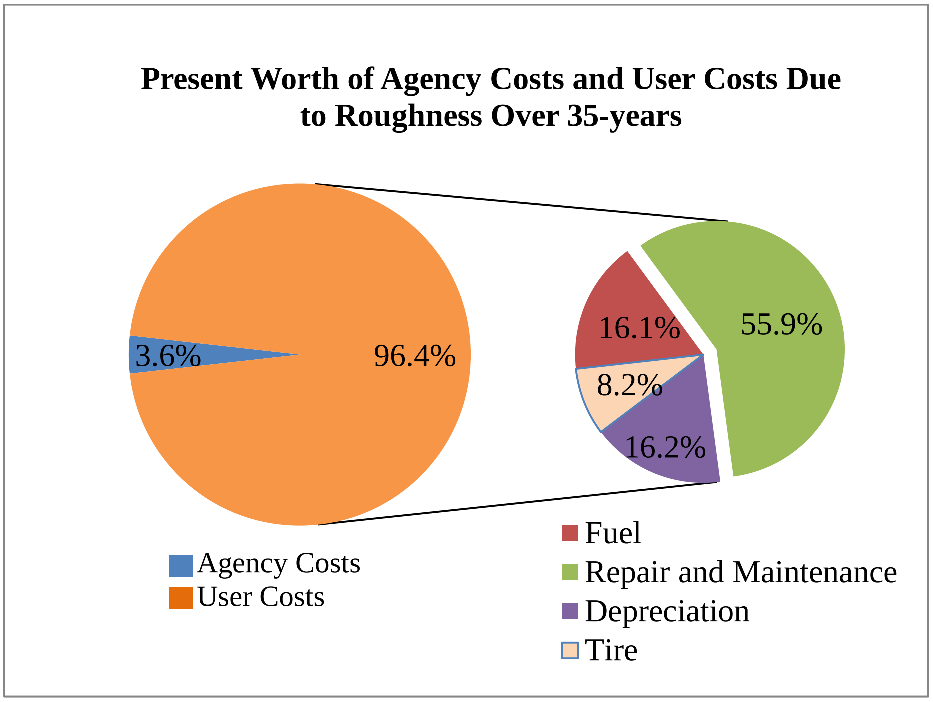

Figure 4.2 Present worth of agency costs and user costs related to roughness over 35-year analysis period of pavement (initial IRI = 63 inch/mile)

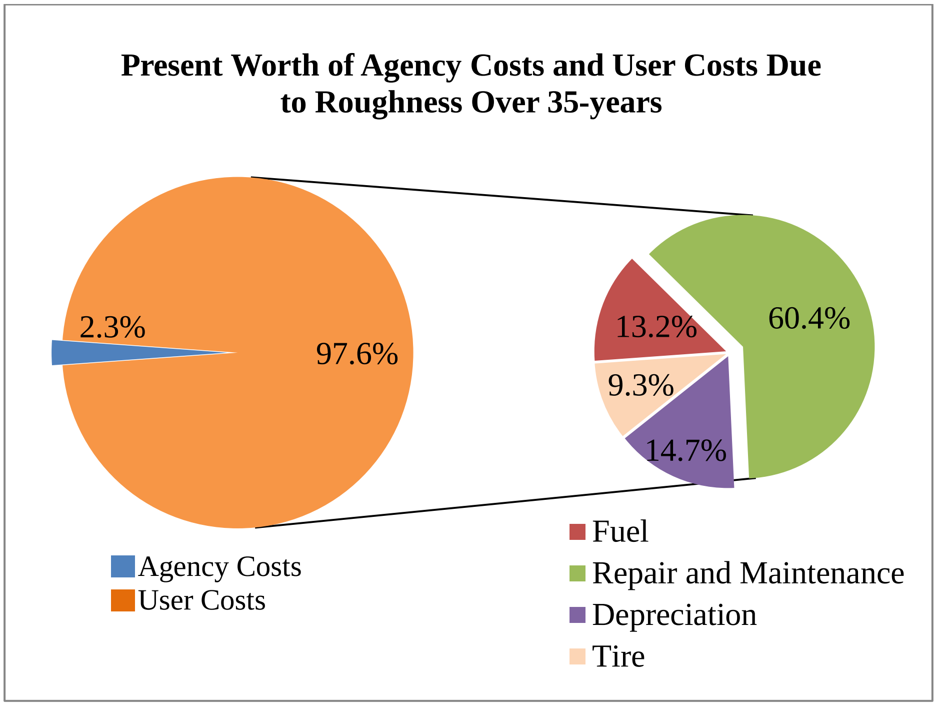

Figure 4.3 Present worth of agency costs and user costs related to roughness over 35-year analysis period of pavement (initial IRI = 70 inch/mile)

The present analysis strongly suggests that increased investment in pavement maintenance and rehabilitation activities aimed at reducing pavement roughness could result in a many-fold savings in user costs. It is acknowledged that the typical values, models and other assumptions used in this study will vary from region to region, and will change with time (e.g., with changes in fuel, material, and vehicle maintenance costs, changes in transportation policies, etc.). A spreadsheet-based program is currently being developed to facilitate the LCCA analysis performed herein, which will allow this model to be readily applied in various regions across the US and abroad. Table 4.3 provides a sensitivity analysis comparing agency vs. user costs for differing average daily traffic (ADT) levels and analysis periods. It was assumed that agency cost would be 10% less and 10% more for 8,000 ADT and 12,000 ADT, respectively compared to 10,000 ADT, to account for full-depth asphalt design pavement thickness variation as a function of design traffic. Although these two variables clearly affect agency and user costs, the overall conclusion of the study (users bear the bulk of the financial burden when pavements become rough) is unchanged.

Table 4.3 Sensitivity Analysis for Traffic Level and Analysis Period

Average Daily Traffic Level and Yearly User Cost			
Traffic Level (ADT)	Agency Cost	User Cost	
		Initial IRI =63 inch/mile	Initial IRI = 70 inch/mile
8,000	$330,400	$7,928,341	$12,368,748
10,000	$367,115	$9,910,426	$15,460,936
12,000	$403,825	$11,892,512	$18,553,123
Analysis Period and Yearly User Cost			
Analysis Period (years)	Agency Cost	User Cost	
		Initial IRI =63 inch/mile	Initial IRI = 70 inch/mile
35	$367,115	$9,910,426	$15,460,936
40	$388,723	$11,345,212	$17,409,807
45	$405,547	$11,561,089	$17,929,249

4.2 Pavement users costs with enhanced M&R

A final analysis is now presented to further demonstrate that increased pavement maintenance activities will be paid off many times over in reduced user costs. Table 4.4 shows the maintenance and rehabilitation strategy used to conduct this analysis. Table 4.5 shows increases in user costs.

Table 4.4 An example of an enhanced maintenance and rehabilitation strategy for a 1-mile section of roadway

Year	Action	Cost		
0	New Pavement	$206712	Present of Worth of Alternative 1	$367,115
3	Crack Seal (4 yrs)	$1,500	Present Worth of this M&R	$475,325
7	2" Mill & 2" Overlay	$94,090	**Additional Investment**	**$108,209**
10	Crack Seal (4 yrs)	$1,500		
13	2" Mill & 2" Overlay	$94,090	Roughness related user costs for Alternative 1 with initial IRI 63 in/mile	$9,910,426
16	Slurry Seal (4 yrs)	$11,265	Roughness related user costs for this M&R with initial IRI 63 in/mile	$4,740,484
20	2" Mill & 2" Overlay	$94,090	**Reduction of user costs**	**$5,169,943**
23	Crack Seal (4 yrs)	$1,500		
26	2" Mill & 2" Overlay	$94,090	Roughness related user costs for Alternative 1 with initial IRI 70 in/mile	$15,460,936
30	2" Mill & 2" Overlay	$94,090	Roughness related user costs for this M&R with initial IRI 70 in/mile	$9,725,724
35	Salvage Value	-$47,045	**Reduction of user costs**	**$5,735,212**
Present Worth (PW) =		$475,325		
EUAC =		$22,121		

Table 4.5 User Costs for the Enhanced M&R Strategy

	Initial IRI of Pavement = 63 inch/mile				Initial IRI of Pavement = 70 inch/mile		
Year	IRI, Inch/mile	Total Increase in User Cost, $/mile	Total Cost per year for 10,000 vehicle, $	Total Cost per Year per vehicle, $	IRI, Inch/mile	Total Increase in User Cost, $/mile	Total Cost per year for 10,000 vehicle, $
0	63	0	$ -	$ -	70	0	$ -
1	76.3	0.000386899	$ 46,428	$ 5	83.3	0.000481	$ 57,709
2	80.1	0.000632008	$ 75,841	$ 8	87.1	0.001986	$ 238,297
3	83	0.000817608	$ 98,113	$ 10	90	0.003124	$ 374,906
4	86.6	0.001788174	$ 214,581	$ 21	93.6	0.004525	$ 543,034
5	89.6	0.002967715	$ 356,126	$ 36	96.6	0.005683	$ 681,909
6	93.5	0.004486547	$ 538,386	$ 54	100.5	0.007173	$ 860,773
7	76.3	0.000386899	$ 46,428	$ 5	83.3	0.000481	$ 57,709
8	80.1	0.000632008	$ 75,841	$ 8	87.1	0.001986	$ 238,297
9	83	0.000817608	$ 98,113	$ 10	90	0.003124	$ 374,906
10	86.6	0.001788174	$ 214,581	$ 21	93.6	0.004525	$ 543,034
11	89.6	0.002967715	$ 356,126	$ 36	96.6	0.005683	$ 681,909
12	93.5	0.004486547	$ 538,386	$ 54	100.5	0.007173	$ 860,773
. . .	. . .	. . .	. . .	. . .	. . .	. . .	. . .
34	86.6	0.001788174	$ 214,581	$ 10	90	0.003124	$ 374,906
35	89.6	0.002967715	$ 356,126	$ 21	93.6	0.004525	$ 543,034
Present Worth (PW) =			$4,740,484	Present Worth (PW) =			$9,725,724

If the enhanced M&R strategy shown in Table 4.4 is used, it would require an additional transportation agency expenditure in terms of present worth of $108,209 more over the 35-year analysis period. According to Table 4.4, this would save a whopping $5,169,943 to $5,735,212 (52% to 37%) of user costs over the 35-year life cycle depending on the initial roughness of the pavement. Stated otherwise, increased maintenance activities resulting in smoother pavement condition over the life of the pavement will have about a 50-fold return on investment in terms of reduced user costs. Additional justification for the increased maintenance expenditures can be argued from a sustainability standpoint; increased pavement maintenance activities will significantly reduce fuel consumption and tire wear over the life of the pavement, and will extend the overall life of pavement system (the enhanced M&R strategy results in a higher salvage value and therefore a higher remaining life in the pavement section at the end of the 35-year analysis period, thereby delaying reconstruction). It is hoped that the present analysis will provide compelling information that can be used by transportation policy makers to make a strong case for increased maintenance and rehabilitation activities to help reduce the financial burden carried by users resulting from rough pavement.

4.3 *Environmental impacts of M&R activities*

According to the National Asphalt Pavement Association (NAPA), annual hot-mix asphalt production in the US is about 500 million tons. About 90% roads and highways are constructed with asphalt concrete (Hansen and Newcomb 2007). According to the Federal Highway Administration (Harrington 2005), annual production of aggregate is about 2 billion tons, but the demand will increase to 2.5 billion tons by 2020. The amount of resources and investment needed to keep the transportation network in good condition, and methods to go about this in a sustainable manner, need to be thoroughly analyzed. Life cycle cost analysis (LCCA) and life cycle assessment (LCA) are powerful tools that can be used to assess economic and environmental impacts associated with resource usage and infrastructure investments. An ideal LCA considers five phases of pavement life, including: materials; construction; use; maintenance and rehabilitation (M&R), and; end-of-life.

Brillet et al. (2006) reported that construction and maintenance of roadways and vehicle operation are not independent. This is because while pavement M&R activities improve the smoothness of roads and, therefore; consumption related to use is decreased, the additional M&R activities required to improve smoothness result in extra consumption and emission. It is evident from a review of the literature that long term assessment of pavement using LCCA-LCA and including agency costs, user costs, and environmental costs is necessary to obtain a holistic evaluation of rehabilitation strategies and sustainable construction approaches.

4.3.1 **Pollution damage cost rates**

Although no standard monetary value has been assigned to various pollutants, many existing studies considered different values for each pollutant. Unit costs of pollutants are estimated based on their impacts on health. Unit cost of pollutants and greenhouse gases depends on population density and land cover of the construction site

(Malela and Sadasivam 2011). It is assumed that the emission of these pollutants and greenhouse gases have a substantial adverse effect on health in metropolitan areas with higher population densities. Thus, unit costs associated with emissions is higher in urban areas than rural areas. Tol (2005) reported that damage cost of carbon dioxide (CO_2) varies in the range of $5-125 per ton, and reported that most estimates are in the lower range. Tol et al. (2001) stated that “estimates [of carbon dioxide emission cost] in excess of $50/ton requires relatively unlikely scenario of climate change, impact sensitivity, and economic values”. Emission damage costs were collected from Kendall et al. (2008) and adjusted to 2011 dollar using consumer price index (CPI). Damage cost was reported by Tol (2003) based on cost effectiveness and cost benefit of various emission and climatic scenarios. In this study, emission damage costs of pollutants and greenhouse gases were obtained from a recent (2011) FHWA report (Mallela and Sadasivam 2011) and Kendall et al. (2008) report (Table 4.6).

Table 4.6 Emission cost rates (Kendall et al. (2008))

	CO_2, tons	NO_X, tons	PM_{10}, tons	SO_2, tons	CO, tons	Pb, tons
Rural Cost Rate, $/ton	26	8712	980	26	0	588
Urban Cost Rate, $/ton	26	8712	7526	208	2	4845

4.4 <u>Emission costs due to M&R activities</u>

Environmental Costs were estimated from emissions generated by various activities related to pavement such as pavement materials production, transportation, and equipments used during construction. Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE) provides emissions of five criteria-pollutants defined by Environmental Protection Agency (EPA) and major greenhouse (CO2) gas (Horvath 2004). The criteria-pollutants include carbon monoxide (CO), nitrogen oxides (NOX), sulfur dioxide (SO2), lead (Pb), and particulate matter (PM10). The PaLATE program estimates emissions resulting from the production of pavement materials, transportation of those materials to the site, and construction processes.

4.4.1 Emission calculation

Life cycle cost analysis and life cycle assessment (LCCA-LCA) were applied to a 1-mile, 1-lane asphalt pavement section. In this study, emissions due to material production, transportation to the construction site, and construction process was obtained by PaLATE. Table 4.7 describes materials, processes, and equipment considered in this study for the CMR activities in the two different approaches investigated.

Table 4.7 Details of material quantities, process, and equipment used for CMR

Stage	Item	Quantity, yd^3		Material Source to Site Distance, mile	Transportation Mode
		Basic Approach	Alternative Approach		
Initial Construction	Virgin Aggregate	2206	2206	20	Dump Truck
	Bitumen	141	141	30	Tanker Truck
	Gravel (Base)	98	98	20	Dump Truck
Maintenance and Rehabilitation	Virgin Aggregate	1256	1917	20	Dump Truck
	Bitumen	70.4	117	30	Tanker Truck
	Asphalt Emulsion	35	17.4	30	Tanker Truck
	RAP Material	782	1955	-	
	Hot-in-Place Recycling (HIPR)	782	1955	-	
	Crack Sealing	0.26	0.19	30	Tanker Truck

Process	**Equipment Used**
HMA Production	Asphalt Mixing in Batch Plant
Asphalt Paving	Paver, Pneumatic Roller, Tandem Roller
Milling	Milling Machine
Crushing Plant	Excavator, Wheel Load, Dozer, Generator
HIPR	Heating Machine, Asphalt Mixer, Pneumatic Roller, Tandem Roller

The PaLATE program accounts for emissions due to all phases of material production. For asphalt production, this includes extraction, transportation/storage, heating, distillation, cooling, and final processing. Emission due to the traffic use phase was estimated by MOVES, which was developed by EPA. Two different traffic levels (10,000 and 15,000 AADT) were considered in both the basic and alternative M&R approaches. Figure 4.4 shows emissions generated by 15,000 passenger cars over 35 years in an urban area along with pavement construction emissions. As initial construction is identical in both basic and alternative approaches, emission is also same. In maintenance phase, CO_2 emission is about 115 tons/mile and 191 tons/mile in the basic and alternative approaches, respectively. Because of the heavier rehabilitation associated with the alternative approach, emissions are higher than those associated with the basic approach. However, CO_2 emissions related to pavement roughness is actually predicted to be less in the alternative approach (240 tons/mile) than the basic approach (325 tons/mile) because of the reduction in vehicle emissions associated with maintaining smoother pavement throughout the analysis period investigated.

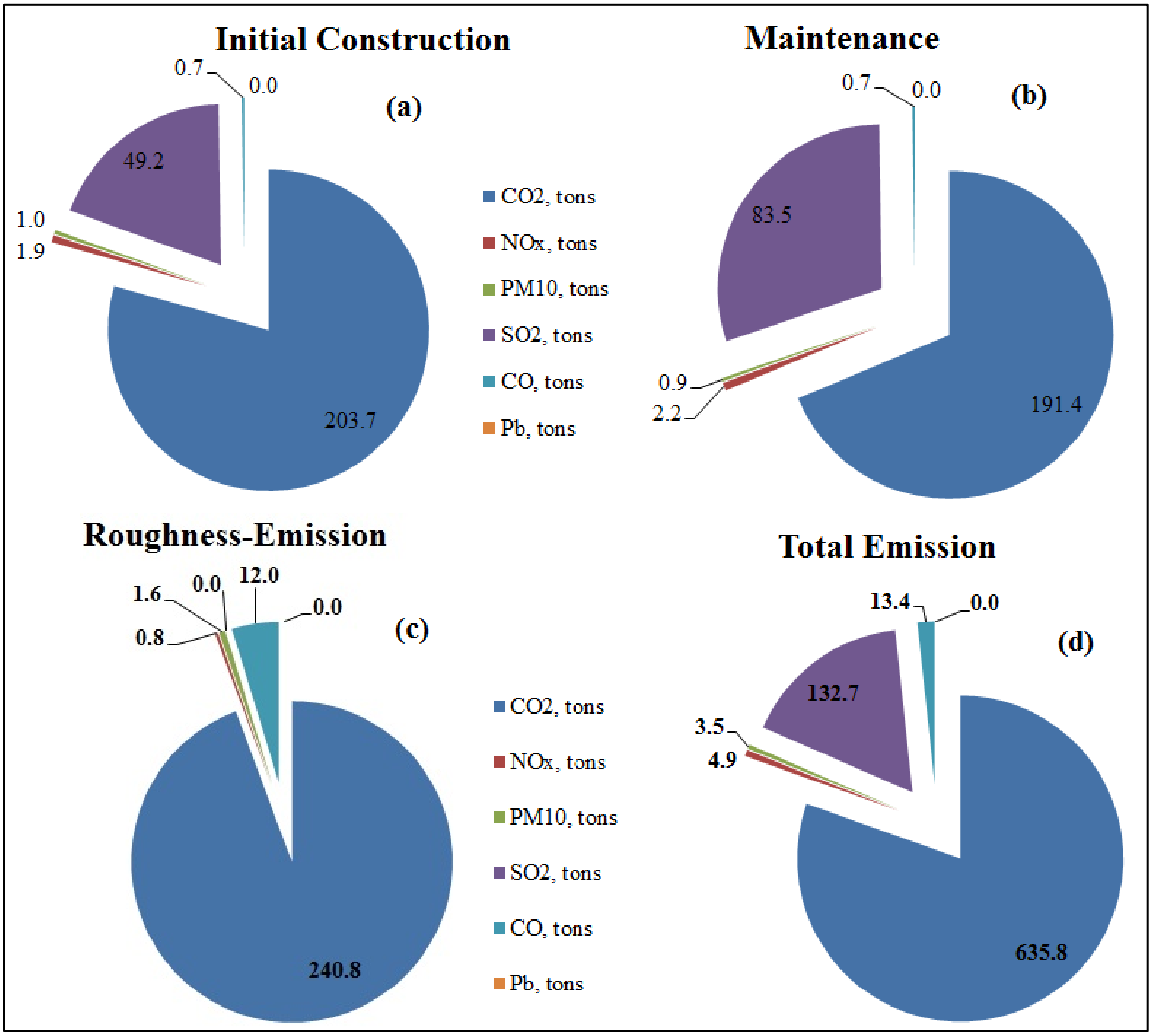

Figure 4.4 Emission of alternative approach for urban area over 35-year pavement service life: (a) initial construction, (b) maintenance, (c) emission due to pavement roughness, and (d) total emission

Zaabar and Chatti (2011) studied the effect of roughness on fuel consumption of vehicles, and reported that fuel consumption increases with pavement roughness and can increase as high as 4 percent depending on IRI level. In the current study, their model was used to estimate additional fuel resulting from pavement roughness. The MOVES program was to calculate rate of emission of air pollutants and greenhouse gases (EPA 2012). This rate was used to estimate emission due to fuel utilized by vehicles due to roughness and is reported in this paper as roughness-related emissions. Pollution damage costs were estimated using rates reported by Kendall et al. (2008). Tables 4.8 and 4.9

show emissions and cost data for urban area for basic and alternative approaches using 15,000 AADT.

Table 4.8 Emissions by category and associated environmental cost: basic approach - Urban area

Emissions Category	CO_2, tons	NOx, tons	PM_{10}, tons	SO_2, tons	CO, tons	Pb, tons
Initial Construction	204	2	1	49	1	0.0002
Maintenance	115	1	1	45	0	0.0002
Vehicles - 35years	87764	292	588	3	4391	11
Roughness Related	325	1	2	0	16	0.04
Total Emissions	88408	296	592	97	4409	11
Est. Envir. Cost, $/ton	26	8712	7526	208	2	4845
Total Environmental Cost, $	$2,274,301	$2,581,150	$4,453,547	$20,261	$10,802	$51,089
					Total =	**$9,391,150**
Portion of Emissions due to Init. Constr. and Maint.	319	3	2	94	1	0.0004
Est. Envir. Cost, $/ton	26	8712	7526	208	2	4845
Cost, $	$8,206	$27,243	$12,095	$19,602	$3	$2
					Total =	**$67,151**
Portion of Emissions due to Roughness	325	1	2	0	16	0.04
Est. Envir. Cost, $/ton	26	8712	7526	208	2	4845
Cost, $	$8,360	$9,421	$13,503	$2	$40	$188
					Total =	**$31,514**

Table 4.9 Emissions by category and associated environmental cost: alternative approach - Urban area

Emissions Category	CO_2, tons	NOx, tons	PM_{10}, tons	SO_2, tons	CO, tons	Pb, tons
Initial Construction	204	2	1	49	1	0.0002
Maintenance	191	2	1	83	1	0.0002
Vehicles - 35years	87764	292	588	3	4391	10.5058
Roughness Related	241	1	2	0	12	0.0288
Total Emissions	88400	297	592	136	4405	10.5350
Est. Envir. Cost, $/ton	26	8712	7526	208	2	4845
Total Environmental Cost, $	$2,274,092	$2,587,036	$4,454,407	$28,301	$10,792	$51,041
					Total =	**$9,405,669**
Portion of Emissions due to Init. Constr. and Maint.	395	4	2	133	1	0.0004
Est. Envir. Cost, $/ton	26	8712	7526	208	2	4845
Cost, $	$10,162	$35,569	$14,307	$27,643	$3	$2
					Total =	**$87,686**
Portion of Emissions due to Roughness	240.82	0.80	1.61	0.01	12.05	0.03
Est. Envir. Cost, $/ton	26	8712	7526	208	2	4845
Cost, $	$6,195	$6,982	$12,150	$2	$30	$140
					Total =	**$25,498**

From Table 4.8 and 4.9, it can be seen that emission of air-pollutants and greenhouse gases in an urban setting are predicted to be higher in the alternate M&R approach than that of the basic approach. Carbon dioxide (CO_2) emission is same for the initial construction phase but higher for alternative approach in maintenance phases and roughness related emission. As more major rehabilitation and maintenance activities were applied in alternative approach, as shown in Table 4.4, emissions are higher in this case. Increases in carbon dioxide and sulfur dioxide emissions in maintenance activities are significant, about 66% and 84%, respectively. But roughness-emission was reduced in the alternative approach as pavement was kept smoother via additional rehabilitation. From Table 4.8 and 4.9, it can be seen that both carbon dioxide and carbon monoxide emissions related to pavement roughness were reduced by 25% in the alternative approach. Vehicle emissions for 15,000 AADT was also estimated over the 35-year analysis period and reported in Tables 4.8 and 4.9. Emissions due to construction and maintenance of pavement are quite low compared to vehicle emissions. Costs associated with emissions were also reported in Table 4.8 and 4.9. Emission costs in the alternative approach due to maintenance and rehabilitation is 30% higher than that of the basic approach over the 35 year service life of the pavement, but roughness-emission cost is about 20% less than that of the basic approach. As a result, it can be seen that pavement smoothness tends to reduce the costs associated with emissions that are generated as a result of the additional rehabilitation required to maintain the higher level of smoothness by about two thirds.

CHAPTER 5. RESULTS AND DISSCUSSION

This chapter summarizes the research, highlights its contributions, and proposes directions for future research.

5.1 Agency investment, users, and emission costs

Agency costs, user costs due to pavement roughness, and emission costs due CRM and roughness are shown in Figure 5.1. From Figure 5.1, it can be seen that emissions cost due to CRM and roughness is only about 1% and 0.3%, respectively, whereas agency cost and user costs are about 5% and 94%. After splitting the user costs, it can be seen that about 54% of these costs are related to vehicle repair and maintenance. As mentioned earlier, an additional agency investment of $108,209 over 35 years can reduce user costs from $9.9 million to $4.7 million with an ROI of about 48-to-1. As a result of these additional agency M&R activities, extra emissions with a cost of about $20,535 are generated, however; the achieved smoothness reduces the roughness emission cost by an amount of $6,016. Clearly, from a user cost standpoint, it is good policy to maintain roads at a high level of smoothness, as millions of dollars are saved for users over the 35 year analysis period, as compared to the very modest additional environmental cost required to maintain the pavement in a smooth condition (difference between $20,535 and & $6,016, or about $14,500). Although the environmental costs associated with the two M & R strategies considered were relatively small as compared to user costs, it was nevertheless important to conduct a thorough LCA to demonstrate that the results presented by Islam and Buttlar (2012) were still applicable when environmental effects were considered. Whereas the study by Islam and Buttlar (2012) reported a potential 50-to-1 ROI as a result of maintaining pavement in a smooth condition, the current study, which includes LCA along with LCCA, indicates that a 48-to-1 ROI can be realized by maintaining smooth pavement.

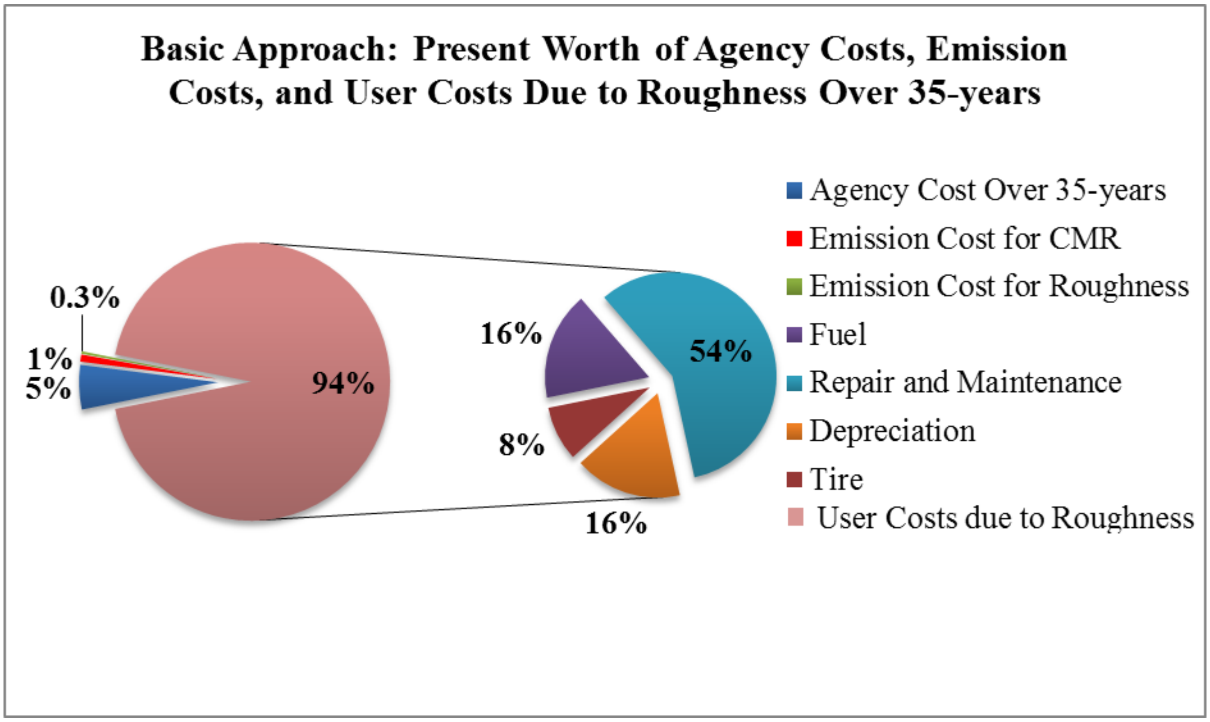

Figure 5.1 Agency costs, emission costs, and user costs due to roughness

5.2 *Importance of pavement smoothness*

Pavement smoothness is very important not only to reduce vehicle repair and maintenance costs but also for safety. Motorists pay significant amount of money because of poor pavement condition. It is a common trend that motorists choose to ride on smoother pavement even if it requires a long detour. Motorists extra expenditure for vehicle repair and maintenances are shown in a map (Figure 5.2), and these data were collected from ASCE report cards.

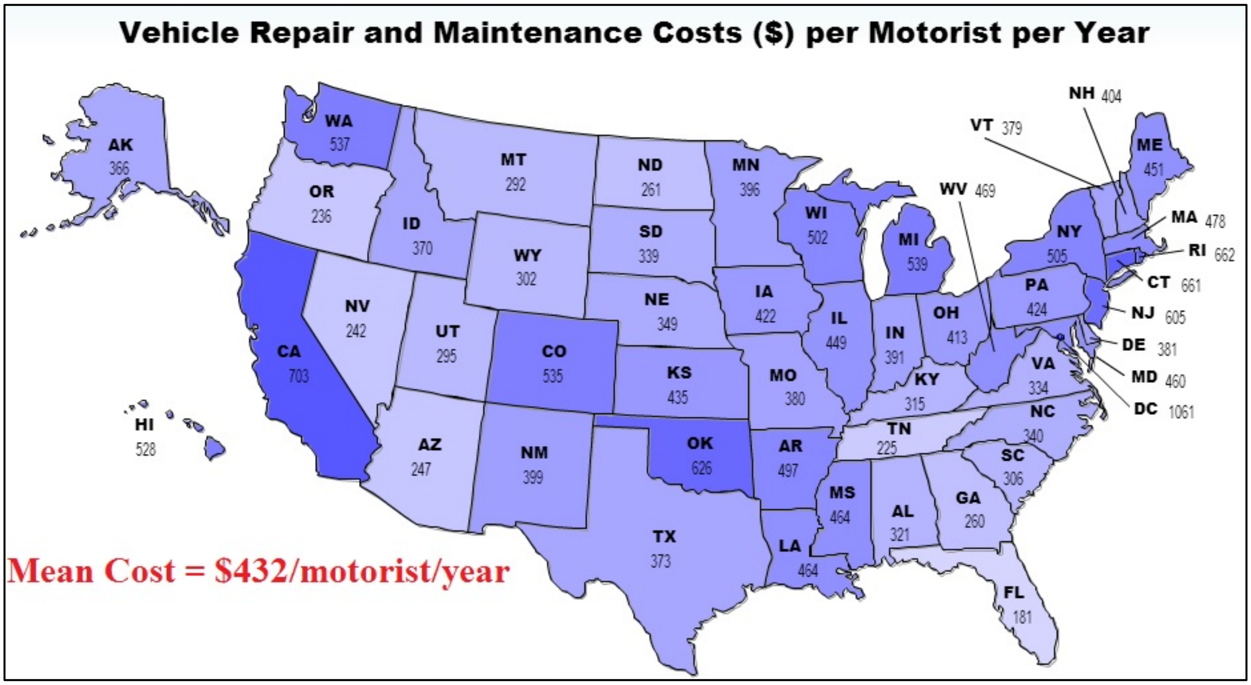

Figure 5.2 Motorists cost for vehicle repair and maintenance per year

CHAPTER 6. SUMMARY, CONCLUSION, AND RECOMMENDATIONS

6.1 Summary

Roughness is an important aspect of pavement condition which significantly affects driver comfort, and moreover, user costs. A comprehensive investigation was conducted to study the effect of pavement roughness on agency and user costs. Some unique features of the research conducted include: (1) A comprehensive array of user costs related to roughness were considered; (2) fuel consumption was computed using a calibrated HDM-4 model; (3) total user costs for a single vehicle and 10,000 AADT was considered for Interstate, primary, and secondary roads; (4) a functional relationship between IRI level and user costs was developed; (5) agency costs were simultaneously considered and compared with user costs in the context of pavement roughness, (6) the newly released MEPDG program was used to predict IRI at different traffic levels and weather condition and with different initial IRI level, and; (7) environmental costs of CMR activities were also considered. The analysis conducted demonstrated that user costs including fuel consumption, repair and maintenance, depreciation, and tire costs dramatically increase with increased pavement roughness, which far outweigh agency costs associated with the construction and maintenance of the facility itself. For the two main examples presented, agency costs based upon typical maintenance practices by state DOTs were in the range of 2.3 to 3.6% of the combined costs (agency plus user) associated with a unit section of roadway.

6.2 Conclusions

It is critically important to maintain pavement in good condition, otherwise, significant user-related costs can be incurred, along with other costs such as those associated with vehicle emissions. From this study, the following conclusions can be drawn:

(a) By investing in additional maintenance (resurfacing every 7 years instead of every 10 years, on average) would save a whopping $5.1 M to $5.7 M (52% to 37%) of user costs over the 35-year life cycle depending on the initial roughness of the pavement, as compared to the additional $108,000.00 agency investment required for this additional rehabilitation step. This equates to a 50-fold return on investment in terms of reduced user costs.

(b) An additional agency investment of $108,209 over a 35-year design period for one mile/one lane of roadway can provide a 48-to-1 return on investment in terms of reduced user costs, when environmental costs are included in the analysis. Still, it can be concluded that maintaining pavement in a smooth condition is an excellent value proposition for the traveling public.

(c) Emission costs associated with additional rehabilitation (maintaining a smooth pavement throughout service life) in the alternative approach were very low compared to savings in user costs that would be realized as a result of maintaining the pavement in a smooth condition.

(d) In the basic approach (pavement allowed to become rough during service life), user costs due to roughness is about $9.9 million (94%) whereas costs to the agency, emission costs due to CMR, and emission costs due to roughness were about $545,491 (5%), $67,151 (1%), and $31,514 (0.3%), respectively, over the 35 year analysis period.

(e) In the alternative approach, which requires an additional $108,210 investment in M & R over the 35 year analysis period, user costs associated with roughness is about $4.7 million (about 52% less than that associated with the basic approach), whereas agency costs, emissions costs due to CMR, and emissions costs due to roughness were calculated as $653,701, $87,686, and $25,498, respectively.

Additional justification for the increased maintenance expenditures can be argued from a sustainability standpoint; increased pavement maintenance activities will significantly reduce fuel consumption and tire wear over the life of the pavement, and will extend the overall life of pavement system.

6.3 Recommendation

Driving comfort and safety are the two most important things that matter for motorists. Pavement roughness in terms of IRI has been widely using in the US as an indicator of driving comfort. It is also an important parameter in pavement design, maintenance, and management decision making process. Pavement materials selection, maintenance and rehabilitation strategies can be modified using roughness information. Currently, a high speed inertial profiler (laser and accelerometer based) system is widely used to collect pavement roughness. This system requires a specialized vehicle with very expensive equipment and trained personnel (sometimes termed “million dollar vans”). Most transportation agencies collect pavement roughness data biennial basis; therefore, pavement maintenance and rehabilitation decisions are made based on a scarcity of current data. With the mobile device revolution, smartphones are equipped with an integrated accelerometer array which can be utilized to estimate pavement roughness by developing a data collection application and analysis scheme. This system can collect data by crowdsourcing, which will provide and up-to-date assessment of pavement conditions, at a lower cost, along with the ability to detect bump features (potholes and buckles or blow-ups) and vehicle swerve maneuvers. We propose this to be the subject of a follow-up NexTrans project.

REFERENCES

AAA Association Communication. Your Driving Costs. AAA, Heathrow, Florida, 2011. http://www.aaaexchange.com/main/Default.asp?CategoryID=16&SubCategoryID=76&ContentID=353. DrivingCosts2011.pdf. Accessed July 15, 2011.

AASHTO. Mechanistic-Empirical Pavement Design Guide. A Manual of Practice, American Association of State Highway Officials, Highway Research Board. Washington, D.C., 2008.

Al-Mansour, A., Sinha, K. C., and Kuczek, T. Effects of Routine Maintenance on Flexible Pavement Condition. Journal of Transportation Engineering, ASCE, Volume 120, Issue 1, 1994.

Barnes, G., and Langworthy, P. Per Mile Costs of Operating Automobiles and Trucks. In Transportation Research Record: Journal of the Transportation Research Board, No. 1824, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 71-77.

Bennett, C. R., and Greenwood, I. D. Volume 7: Modeling Road User and Environmental Effects in HDM-4, Version 3.0. International Study of Highway Development and Management Tools (ISOHDM), World Road Association (PIARC), 2003.

Brillet, F., A. Jullien, and S. Sayagh. Assessment of Consumptions and Emissions during Pavement Lifetime. In Transport Research Arena Europe 2006, TRA, Gotenborg, Sweden, 2006.

Chatti, K., and I. Zaabar. New Mechanistic-Empirical Approach for Estimating the Effect of Roughness on Vehicle Durability Transportation Research Record: Journal of the Transportation Research Board, Vol. 2227, 2011, pp. 180-188.

Chesher, A., Harrison, R., and Swait, J. D. Vehicle Depreciation and Interest Costs: Some Evidence from Brazil. Proceedings of the Second World Conference on Transport Research, London, England, 1981.

Federal Highway Administration (FHWA). Highway Finance Data Collection, Our Nation's Highways: 2010.

http://www.fhwa.dot.gov/policyinformation/pubs/hf/pl10023/fig5_1.cfm. Accessed July 20, 2011.

Federal Highway Administration (FHWA). Our Nation's Highways: 2008. Figure 6-7. Highway Construction Price Trends and Consumer Price Index. U.S. Department of Transportation, 2011.

http://www.fhwa.dot.gov/policyinformation/pubs/pl08021/fig6_7.cfm. Accessed July15, 2011.

Federal Highway Administration (FHWA). Highway Economic Requirements System Technical Manual, U.S. Department of Transportation, Washington, D.C., 2002.

Hall, K. T., Correa, C. E., and Simpson, A. L. LTPP Data Analysis: Effectiveness of Maintenance and Rehabilitation Options. NCHRP Project 20-50[3/4], 2002.

Hall, K. T., and Correa, C. E. Estimation of Present Serviceability Index from International Roughness Index. In Transportation Research Record: Journal of the Transportation Research Board, No. 1655, Transportation Research Board of the National Academies, Washington, D.C., 1999, pp. 93–99.

Hansen, K., and D. Newcomb. RAP Usage Survey. National Asphalt Pavement Association, Lanham, MD, 2007.

Haugodegard, T., Johansen, J., Bertelsen, D., and Gabestad, K. Norwegian Public Roads Administration: A Complete Pavement Management System in Operation. Proceedings of Third International Conference on Managing Pavements, Volume 2, San Antonio, Texas, May 22-26, 1994.

Harrington, J. Recycled Roadways. Public Roads, Vol. 68, No. 4, 2005, pp. FHWA-HRT-05-003.

Horvath, A. Life-Cycle Analysis Model and Decision-Support Tool for Selecting Recycled Versus Virgin Materials for Highway Applications. RMRC Research Project No. 23, Recycled Materials Resource Center, Durham, New Hampshire, 2004.

Islam, S., and W. Buttlar. Effect of Pavement Roughness on User Costs. Transportation Research Record: Journal of the Transportation Research Board, Vol. 2285, 2012, pp. 47-55.

Kendall, A., G. A. Keoleian, and G. E. Helfand. Integrated Life-Cycle Assessment and Life-Cycle Cost Analysis Model for Concrete Bridge Deck Applications. Journal of Infrastructure Systems, Vol. 14, No. 3, 2008, pp. 214-222.

Lu, X. P. Effects of Road Roughness on Vehicular Rolling Resistance. Measuring Road Roughness and Its Effects on User Cost and Comfort (T. D. Gillespie and M. Sayers, eds.), ASTM Special Technical Publication 884. American Society for Testing and Materials, Philadelphia, Pa., 1985, pp. 143–161.

Mallela, J., and S. Sadasivam. Work Zone Road User Costs. FHWA-DTFH61-06-D-00004, Federal Highway Administration, Washington, DC, 2011.

Papagiannakis, A. T., and M. Delwar. Methodology to Improve Pavement-Investment Decisions. Final Report to National Cooperative Highway Research Program for Study 1-33, Transportation Research Board, Washington, D.C., 1999.

Perera, R. W., and Kohn, S.D. Ride Quality Performance of Asphalt Concrete Pavements Subjected to Different Rehabilitation Strategies. ASCE Proceedings of 2006 Airfield and Highway Pavements Specialty Conference, Atlanta, Georgia, April 30 – May 3, 2006.

Sinha, K. C. and Labi, S. Transportation Decision Making: Principles of Project Evaluation and Programming. John Wiley & Sons, Inc., New York, 2007.

Tol, R. S. J. The Marginal Damage Costs of Carbon Dioxide Emissions: An Assessment of the Uncertainties. *Energy Policy,* Vol. 33, No. 16, 2005, pp. 2064-2074.

Tol, R. S. J. Is the Uncertainty about Climate Change Too Large for Expected Cost-Benefit Analysis. *Climatic Change,* Vol. 56, 2003, pp. 265-289.

Tol, R. S. J., T. E. Downing, S. Fankhauser, R. G. Richels, and J. B. Smith. Progress in Estimating the Marginal Costs of Greenhouse Gas Emissions. Research unit Sustainability and Global Change, Hamburg University, 2001.

Transportation Research Board Special Report 286. Tires and Passenger Vehicle Fuel Economy - Informing Consumers, Improving Performance. Transportation Research Board, Washington, D.C., 2006.

U.S. Environmental Protection Agency. Motor Vehicle Emisiion Simulator (MOVES). , Vol. MOVES2010b, 2012.

U.S. Environmental Protection Agency (EPA). Fuel Economy Guide – Model Year 2010. Retrieved From: http://www.fueleconomy.gov/feg/pdfs/guides/FEG2011.pdf. Accessed April 15, 2011.

Von Quintus, H. L., Eltahan, A., and Yau, A. Smoothness Models for Hot-Mix Asphalt–Surfaced Pavements Developed from Long-Term Pavement Performance Program Data. In Transportation Research Record 1764, TRB, National Research Council, Washington, D.C., 2001, pp. 139–156.

Zaabar, I., and K. Chatti. Calibration of HDM4 Models for Estimating the Effect of Pavement Roughness on Fuel Consumption for US Conditions. In Transportation Research Record: Journal of the Transportation Research Board, No. 2155, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 105–116.

Zaniewski, J.P. Effect of Pavement Surface Type on Fuel Consumption; Portland Cement Association: Skokie, IL, 1989.

Zaniewski, J. P., Butler, B. C., Cunningham, G., Elkins, E., Paggi, M. S., and Machemehl, R. Vehicle Operating Costs, Fuel Consumption, and Pavement Type and Condition Factors. FHWA-PL-82-001. FHWA, U.S. Department of Transportation, 1982.