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**Threshold-based resurfacing policies in pavement management to minimize
costs and greenhouse gas emissions**

by

Allan Ogwang

A dissertation submitted in partial satisfaction of the

requirements for the degree of

Doctor of Philosophy

in

Engineering - Civil and Environmental Engineering

in the

Graduate Division

of the

University of California, Berkeley

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Fall 2016

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costs and greenhouse gas emissions**

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Allan Ogwang

Abstract

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Doctor of Philosophy in Engineering - Civil and Environmental Engineering

University of California, Berkeley

Professor Samer Madanat, Co-Chair

Professor Arpad Horvath, Co-Chair

There is an increasing need for the reduction of greenhouse gas (GHG) emissions resulting from pavement maintenance activities, which account for millions of tons of GHG emissions annually. By optimizing pavement resurfacing activities, there is potential for reducing the carbon footprint associated with pavements and users of pavements. We propose a framework for estimating the relationship between GHG emissions from pavement resurfacing activities and pavement cracking-threshold policies. Cracking threshold is defined herein as the maximum percent cracking level a pavement is allowed to reach before an asphalt overlay is applied. In this framework, a probabilistic model capable of predicting both crack initiation and progression over time for individual pavement segments is formulated. The model is applied to a population of pavement segments and, given a cracking-threshold value, can predict the amount of GHG emissions and costs incurred due to resurfacing activities over a specified planning horizon. The model also predicts the corresponding user costs and emissions. In order to obtain the relationship between cracking threshold and GHG emissions, the cracking threshold is varied within a practical range of values. We obtain the corresponding resurfacing interval from which GHG emissions values are computed. The dataset used in the case study is obtained from the Washington State Department of Transportation (WSDOT) in the United States. The results show that the optimal cracking thresholds for minimizing costs and GHG emissions are close to each other, and are both higher than those used currently by WSDOT.

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Chapter 1

Introduction

1.1 Overview

The Intergovernmental Panel on Climate Change (IPCC) found that in order to have at least a 66 percent chance of limiting global warming to, or below, 2°C above pre-industrial levels, no more than 1 trillion tons of carbon can be released into the atmosphere from the beginning of the industrial era through the end of this century [Freedman, 2012]. With two thirds of the emissions budget already spent by 2014, intensive carbon-reduction measures will have to be implemented to keep within desired limits.

Transportation emissions contribute 13% to the global and 28% to the US emissions [EPA]. The emissions due to maintenance and rehabilitation actions on pavements (as a fraction of total transportation emissions) are in the ranges of 5 – 10 percent for heavily trafficked highways and 20 – 50 percent for medium trafficked highways [Horvath, 2008]. While acknowledging the importance of more research and innovation in sustainable fuels and vehicle technologies, pavements could also be important players in the reduction of transportation emissions [Santero and Horvath, 2009].

Pavement management decisions are currently based on economic factors, and rightly so as the user costs tend to increase with the deterioration of road condition [RC, 2015]. In this research, we propose a framework for estimating the relationship between greenhouse gas (GHG) emissions and costs from pavement resurfacing activities and pavement cracking-threshold policies. The term ‘cracking threshold’ is defined herein as the maximum percent cracking level a pavement is allowed to reach before an asphalt overlay is applied.

1.2 Research problem

It is known that allowing vehicles to traverse overly cracked pavements will increase their rolling resistance and therefore incur additional fuel consumption leading to increase GHG emissions, as well as increasing vehicle operating costs [Menzies, 2006]. This provides motivation for a transportation agency to periodically repave the highway pavements under its

jurisdiction to reduce GHG emissions in the transportation sector. However, the repaving activity is also associated with its own GHG emissions externalities, therefore the agency is faced with a dilemma of finding the best criteria of minimizing system-wide GHG emissions and potentially costs.

Cracking is one of the three main pavement distresses (the others being roughness and rutting) by which agencies base their pavement management decisions. There have been studies (for example; [Reger et al., 2014]) that have quantified the pavement roughness level that would be optimal at GHG emissions reduction. However, no study has been done which determines the trigger levels of cracking for a transportation agency to adopt as policy for optimal GHG or cost reduction in the transportation sector.

This study answers the question: “How should pavement cracking trigger thresholds be set to minimize GHG emissions in pavement management?” The transportation agency might be interested to determine the optimum pavement-resurfacing frequency in order to meet GHG emission budgets or to limit agency spending within a given period of time. This research aims to set pavement cracking-threshold policies to achieve such objectives.

The results of the proposed analytical framework will provide information useful to decision makers who are determined to find appropriate GHG emissions reduction measures. It is possible that the pavement rehabilitation policy changes may not be appropriate and within the scope of the current mitigation strategies, but will provide greater incentives for agencies to find better strategies that would lead to GHG emissions reduction.

1.3 Research objective

This research provides an analytical framework by which an agency could use to optimize emissions and cost reduction in asphalt pavement management using cracking as a trigger distress. Under this approach, the agency is able to simulate the entire crack evolution process from the time they appear on the road pavement (crack initiation) to the point at which they attain the set limit (cracking threshold). The approach we take is representative for an agency that seeks to obtain an estimate of the GHG emission reduction potential of its pavement management policies and make comparison with alternative emissions-reduction strategies. In the literature, there are studies that have sought to minimize GHG emissions or costs using roughness as the trigger distress, but no studies have optimized resurfacing activities using cracking as trigger distress. This new approach can help a transportation agency or government make budget decisions with an estimate of the expected GHG emissions from the planned activities for a longer planning horizon using cracking as a trigger distress.

1.4 Research scope

The direct application of this research is to Washington state. The extent to which case study results are generalizable depends on the similarity of particular pavement segments to those in Washington state (in terms of traffic loading, pavement thickness, and weather variables). The developed analytical framework has specifically been designed to be flexible and able to accommodate a wide variety of pavement segments. Thus, the developed analytical framework can be applied to almost any pavement segment anywhere in North America with relevant adjustments to input model parameters. Since European pavements and those of developing countries are fundamentally different, application to those settings will have to be further investigated.

This research is based on traditional hotmix asphalt overlay applications. Although several new pavement technologies are currently being investigated or are in use, hotmix asphalt overlays are still the most common. The temporal scope is for ten years including 2016 as the base year and all costs are expressed in 2016 U.S. dollars.

The terms rehabilitation and resurfacing are used interchangeably for the process by which a new asphalt overlay is placed onto a cracked pavement. Not included in the analysis are minor maintenance activities such as crack sealing, filling or patching. These activities are assumed to be accounted for in the overall deterioration model (crack progression model) for the pavement. Also excluded from the analysis is complete pavement reconstruction, which involves capital expenditures, the complete removal and replacement of all asphalt, base, and sub-base layers of the pavement.

There are several GHG sources associated with pavements. The scope of this research includes materials, transportation, and onsite construction equipment, and emissions due to pavement roughness. The metric is Global Warming Potential (GWP) and the unit is one metric ton of CO₂ equivalent emissions per lane-km.

Delays due to traffic have been shown to have an effect on emissions [Santero and Horvath, 2009]. However, for many regions in Washington state, WSDOT applies overlays at night specifically to mitigate traffic delay. Additional fuel consumption for rerouting or delays is speculative and has not been considered in this study.

For the user emissions and costs, we considered vehicle fuel consumption, vehicle maintenance, and tire wear. Excluded are the roughness effects on goods damage, vehicle speed, and comfort level. Because ride comfort increases when a pavement becomes smoother, it is possible that vehicle speeds might increase on a smoother pavement. However, Wang et al. [2014] found that pavement roughness has a low impact in free-flow speed. This indicates that making a rough pavement segment smoother through application of a maintenance or rehabilitation treatment will not result in substantially faster vehicle operating speeds, therefore the benefits from reduced energy use and emissions due to reduced rolling resistance will not be offset by the increased fuel consumption that accompany increases in vehicle speed (above the optimal range of 40-50 mph or 64-80 kph).

Chapter 2

Literature Review

2.1 Introduction

Cracking is one of the three main distresses considered in pavement management, others being roughness and rutting. Cracks appear in different forms on the pavement and they are categorized according to their appearance and orientation on the pavement. The common categories among asphalt pavements are longitudinal, transverse, fatigue, block, reflection, slippage, and edge cracking [Asphalt Institute, 2016]. Fatigue cracks are caused by repeated traffic loading and constitute the largest proportion of cracked areas among the pavement segments analyzed in this research.

It is important to note that cracking is the initializing distress in the pavement deterioration process and leads to other distresses such as rutting and roughness. Roughness is a compound measure of a pavement's road profile which may include several pavement distresses such as cracking, rutting, raveling, and potholes. Roughness is also the most widely researched distress, and the following section will further elaborate as to why this is the case, and will also provide insight about the need for the transition to cracking as a trigger distress for pavement rehabilitation.

The review of the existing literature pertaining to pavement management is organized as follows. The first subsection discusses pavement roughness and its relationship to pavement cracking. We then describe pavement cracking and how it is better suited as a trigger distress for pavement management. Thereafter, the agency and user costs are defined, and descriptions of the various cost categories included accordingly. A summary of the pavement cracking models is provided for both the crack initiation and progression phases. What follows is a discussion on pavement management strategies and the current trends in pavement optimization. We then review the existing pavement degradation models, and lastly we present a discussion on optimization techniques used in the field of pavement maintenance and rehabilitation decision making.

2.2 Roughness

There is increasing need to clearly specify the goals for pavement management and specifically how those goals can be achieved to convince the transportation agency that the implementation of such systems is in the best interest of both the public and the transportation agencies. In 1980, only five states, Arizona, California, Idaho, Utah, and Washington, were reported to be in various stages of development of systematic procedures for managing pavement networks on a project-by-project basis [Finn, 1998]. By now, all 50 states, the District of Columbia, and Puerto Rico have some form of pavement management programs in place or in development.

In many respects, the beginning of pavement management systems started with the AASHTO Road Test from 1956 to 1960. The road test staff determined that it would be necessary to evaluate the performance of pavements in a way that would be independent of pavement type and that could have universal application for describing a pavement's condition. The method developed and used at the road test is based on a pavement's present serviceability (riding comfort). The concept of riding comfort, as reflected in measurements of roughness or profile, to estimate performance remains the keystone of most PMS although not always the primary triggering factor to initiate maintenance or rehabilitation.

The measurement of roughness and its relationship to riding comfort has been the subject of millions of dollars of research since the completion of the road test. Much of this research has been directed to developing better ways to measure roughness or some response to roughness that can provide more reliable estimates of riding comfort. This effort will no doubt continue. The International Roughness Index (IRI) is the principal method used to measure roughness and to relate it to riding comfort.

Roughness is defined in accordance with American Society for Testing and Materials (ASTM) E867 as "The deviation of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics and ride quality." The values of roughness are expressed as the IRI in the unit of total vertical displacement in meters per unit distance, usually a kilometer long section (m/km).

While many agencies use IRI to measure ride quality, they use several types of equipment to measure IRI. In addition to the variation in equipment, the method of measurement is not consistent, some measure the right side wheel path only, some the left-side only, some report only the worst, and some average values from both wheel paths.

If the agencies are to adopt performance-specified maintenance contracts (PSMC) for pavement management activities, the accuracy and reproducibility of roughness data becomes very crucial. Continuity of the service providers and their respective equipment (given the fact that most service providers are vertically integrated) is key to obtaining repeatable results. However, in many instances, changes in the service providers have led to significant changes in overall network figures in subsequent years. This makes a lot of data unusable due to the difficulty in correlating the results from two different instruments in the subsequent years. And this is essentially what happened with roughness measurements for both Caltrans and WSDOT making lots of historical data obsolete, hence slowing down the formulation of

more advanced pavement distress models.

Roughness is measured in network surveys using either profilometers or response type road roughness measuring systems. The responsibility for calibration of the equipment resides with the service provider, however this is not usually mandated leaving no possible grounds for determining the correlation between the old and new data collected using a different equipment.

Among the different classes of instruments used to measure roughness, Morrow [2006] found that some instruments significantly underestimated the roughness on rougher surfaces, such as the Riley instrument, when compared to the Walking profilometer and Z-250 reference profiler.

Many agencies use roughness as a key distress for specifying pavement maintenance policy. Trigger roughness values are in accordance with the agency's specific goals and funding availability as a decision making support criterion. Different agencies end up having differing trigger roughness values (for example; Caltrans uses an IRI of 2.7 IRI (m/km) [Reger et al., 2014], while Arizona DOT uses 4.0 - 4.4 IRI (m/km) [Zaghloul et al., 2006]). The difference might be due to differing pavement condition goals and funding sources, but another likely reason could be the differences in roughness measurement equipment. This impedes the direct comparison of pavement performance parameters and makes learning from each other much more difficult.

Also acceptable ranges of IRI differ significantly for different states and has been shown to be anywhere from 450 inches per mile (7.09 meters) to 45 inches per mile (0.71 meters) [Finn, 1998]. It would seem clear that the major causes of these differences are related to the different equipment used and the different methods of measurement. Such differences in equipment, methods of measurement, and reporting make it difficult to compare information and to share experience, and to work together for improvements. This adds to the challenges involved with using roughness as the trigger distress for pavement maintenance.

It would be beneficial if all the transportation agencies were measuring, summarizing, and reporting comparable information. This would facilitate communications, and it would enable collaboration in data collection and analysis for which the resulting information would be more valuable than the individual parts summed.

2.3 Pavement cracking

Cracks appear on many pavements and occur in several forms. Cracks on a pavement are very noticeable by a road user, and progression of their severity can be observed over time as one traverses a road. There are several types of cracks on asphalt pavements which include fatigue, block, longitudinal, transverse, and edge cracking. The type of cracking that is highly correlated with traffic loading is fatigue cracking, and it is the type that is further explored in this research. Other contributing factors to fatigue cracking include weak surface, base and subbase layers, thin surface layer and/or poor drainage [Asphalt Institute, 2016].

As transportation agencies seek to improve pavement condition survey methods, automated machines are gradually replacing traditional visual surveys due to the advancements in computer imaging technologies in the past two decades [Varadharajan et al., 2014]. Cracking survey manuals have been based on the ability of human surveyors to subjectively recognize distresses by identifying crack patterns in various locations on the pavement surface. New imaging technologies are able to capture images with precise location identification which can be input into computer algorithms to objectively categorize the cracking distresses with much less bias.

Cracking survey measurements are calculated as the ratio of the total length of crack in the wheel paths divided by the length of the pavement segment. Also included in the measurement is the severity of the cracks, which is indicated by the widths of the cracks. Crack lengths increase in both severity and length over time, therefore, total crack length is a good proxy for crack severity. In this research, the cracking level is measured in percent cracking, which is the ratio of total crack lengths in the wheel paths (fatigue cracking) to total pavement segment length.

2.4 GHG emissions and costs associated with pavement resurfacing

Asphalt pavements that have achieved a set distress level (trigger threshold) are repaired with an asphalt overlay. However, during the life of the pavement, transportation agencies apply routine maintenance activities including crack sealing and crack filling. The objective of any crack treatment is to minimize the intrusion of water into the underlying layers of the pavement structure. The crack treatments prevent water infiltration into the base layers of the pavement [Decker, 2014], which might reduce pavement structural failures.

In this study, asphalt overlay activity was considered. A study by Santero [2009] estimated GHG emissions attributable to pavement overlay activities using a life-cycle assessment (LCA) approach, and these were directly applied in the simulations described in the methodology section. LCA takes into account the materials used in making asphalt concrete, as well as the activities involved with moving the raw materials from the extraction sites to the hot-mix asphalt plant and the processed asphalt concrete from the hot-mix asphalt plant to the construction site. It also includes the asphalt overlay placement activity in terms of the equipment and fuel used.

The costs for overlay application were obtained considering two major processes, i.e., excavation of surface layer and placement of asphalt layer. The costs, delineated by the thickness of the overlay, were obtained from previous estimates of the asphalt overlay costs for WSDOT as well as estimates for surface excavation. Asphalt bid prices for previous years were used as cost estimates for the asphalt placement activity. Although the bid prices are marked up from the real costs of the asphalt placement activity, they are a good proxy for the cost of overlay placement (given the fact that it is what the agency pays for the overlay

placement activity).

2.5 Pavement Management

A Pavement Management Systems (PMS) can be defined as a decision-support tool that provides decision-makers in highway agencies with optimum strategies for maintenance of the pavement assets [Haas et al., 1993]. An ideal pavement management system would yield the best possible value (benefit) for the available funds while providing and operating smooth, safe, and economical pavements [McWaters and Sharpe, 1995].

Pavement management involves the identification of optimum maintenance strategies and the implementation of these strategies [Haas et al., 1993]. It is a process that covers all the activities involved in providing and maintaining pavements at an adequate level of service. Several research papers [Golabi et al., 1982, Shahin and Kohn, 1982, Mbwana and Turnquist, 1996, Sathaye and Madanat, 2011] have detailed how to develop and attain a functional PMS. However, the main objectives of the optimization criteria implemented in these systems is to minimize agency costs while maintaining the best possible conditions. With the awareness of the environmental impacts of pavement management activities [Santero, 2009], development of a PMS that considers environmental aspects has become an important goal.

2.6 Pavement Deterioration Models

Pavements are complex structures whose distress evolution is due to several factors such as traffic loading, age, materials, and environmental factors. The literature contains several models that relate pavement condition to the variables above [Madanat et al., 2002]. The basic measures of pavement condition are distress indicators that can be classified as either structural or functional indicators. Structural performance is related to the load-carrying capacity of the pavement, while functional performance relates to serviceability or safety.

There are two common types of pavements, that is rigid and flexible pavements. This research focuses on the latter. Flexible pavement structural distresses may include rutting, cracking and potholes, while functional distresses include roughness and skid resistance. Most of these distresses are interdependent, such as cracking influencing pothole growth which in addition to raveling and rutting lead to rough surfaces.

It has been known for a long time that fatigue cracking is the most prevalent form of structural distress of flexible (asphalt concrete) pavements [Finn, 1973]. In recent studies, e.g., Dong and Huang [2012], cracking is mentioned as the most critical distress in the asphalt surface layer among the various types of pavement distresses. Cracking allows moisture infiltration, increased roughness and further deterioration, hence making other distresses more severe. Several transportation and highway agencies use cracking as one of the main two distresses (the other being roughness) as a trigger for pavement rehabilitation [SML, 2010].

In order to minimize the life-cycle emissions and costs of pavements, the awareness of the thresholds at which pavements should be rehabilitated, subject to emissions and financial budgets, is important. To determine these thresholds, agencies need to predict the initiation and progression of distresses for their pavements.

Several models that can predict the initiation and progression of asphalt pavement cracking have been developed [Nakat and Madanat, 2008, Madanat et al., 2010, Reger et al., 2013]. Most of these models predict either the cracking initiation phase or the progression phase, with one exception [Madanat et al., 2010]. Crack initiation models are typically stochastic duration models, where the dependent variable is the probability distribution of the time to cracking. Crack progression models are regression models where the estimation sample consists of pavements that have cracked. In this research, the two processes are combined, which allows for the prediction of the entire life of a pavement after rehabilitation.

2.7 Pavement Rehabilitation Optimization

Due to the aging of the roadway system in many countries, the number of roadway lane kilometers in need of pavement rehabilitation is increasing. To meet the growing travel demand and the public's expectations for safety, ride quality, and traffic flow, road agencies are redefining their objectives to focus on activities and strategies to preserve and maintain existing highway systems, without exceeding the agency cost budget and with minimum impact to the environment. This requires the development of pavement management systems which can solve for optimal pavement rehabilitation frequencies, subject to agency costs and GHG emissions constraints.

Existing pavement management systems (PMS) have been developed using one of two approaches, top down and bottom up. In the top-down approach, the PMS solves for maintenance and rehabilitation policies for an entire network to provide a system level optimum for the desired objective (maximize serviceability or minimize societal costs). Golabi et al. [1982] were the first to apply this approach in pavement maintenance and rehabilitation optimization for the Arizona state system of pavements. This approach allows for integration of management policy decisions and budgetary policies, and produces solutions at the aggregate level, rather than at the facility level.

In the bottom-up approach, the PMS first produces facility level optimal policies and thereafter combines these facility-level policies within the available budget constraints. An example of bottom-up policies is given in Sathaye and Madanat [2012], who solved a multi-facility resurfacing problem using this approach. The bottom-up approach has the advantage of providing facility-specific solutions. Because of this feature, we chose to use a bottom-up approach in our research.

Li and Madanat [2002] found that the optimal pavement resurfacing policy for a long-term planning horizon has a threshold structure. The authors used roughness as the trigger distress. However, using roughness as the distress that triggers a rehabilitation activity is not

necessarily the best alternative, as roughness tends to be the lagging distress that appears at the tail-end of other distresses such as cracking, raveling, and rutting [SML, 2010].

Reger et al. [2014] and Reger et al. [2015] proposed a framework for optimizing pavement resurfacing policies with two criteria: societal costs and greenhouse gas emissions. The authors describe a Pareto frontier that is a range of potentially optimal decisions where it is not possible to decrease total emissions without increasing total costs, using roughness as the trigger distress for rehabilitation. The authors, however, did not account for the initiation of the other distresses, such as cracking, which are components of roughness.

Chapter 3

Methodology

3.1 Introduction

In this section, we present a unifying framework that incorporates both the initiation and progression phases of pavement cracking. The framework involves the use of Monte Carlo simulation to determine the expected time for crack evolution from the point at which a new overlay is applied to the time it attains a predetermined cracking-threshold for a pavement segment. We then show how the optimal cracking threshold resurfacing policies were determined according to costs and GHG emissions considerations separately. The user cost and emissions were determined and included in the framework, thereby evaluating the effect of system wide policies to both the agency and the road users.

The notation in the text is as follows; standard variables are denoted by lower-case letters, e.g. “ x ”. Realizations of random variables are denoted as ‘ \hat{x} ’. Vectors are denoted by upper-case letters, “ X ”, matrices are represented by bold characters, “ \mathbf{X} ”, and sets are represented by calligraphic letters “ \mathcal{X} ”.

3.2 Analytical framework

Given a discrete time point $t \in \mathcal{T} = \{0, 1, \dots, p\}$ whereby p is the length of the planning period, and a pavement segment $i \in \mathcal{I} = \{1, 2, \dots, n\}$, the corresponding GHG emissions resulting from an asphalt overlay activity on pavement segment i at time t are denoted by $g_{i,t} \in \mathbb{R}^+$. At a system level, the GHG emissions for the entire population of pavement segments \mathcal{I} and a specified planning period p is defined by

$$G_{\mathcal{I},p} = \sum_{t=0}^p \sum_{i=1}^n g_{i,t} \cdot a_{i,t} \quad (3.1)$$

where $a_{i,t} \in \{0, 1\}$ is an indicator function defined by the *pavement rehabilitation policy*. In this research, the pavement rehabilitation policy entails applying a thin overlay (in the

range of 0.06-0.30 ft) to the pavement segment when the cracking level, $c_{i,t} \in \mathbb{R}^+$ exceeds a pre-defined threshold value $\phi_c \in \mathbb{R}^+$, so that

$$a_{i,t} = \begin{cases} 1, & \text{if } c_{i,t} > \phi_c \\ 0, & \text{otherwise} \end{cases} \quad (3.2)$$

The cracking level of a given pavement at a given time is estimated using a *unified pavement cracking model*, $Q_k(c_{i,t-1}, V_{i,t-1}, B_{t-1,k})$, where the index $k \in \{0, 1\}$ refers to either the crack initiation (0), or the crack progression model (1).

The details of the crack initiation and crack progression models are described in Nakat and Madanat [2008], Madanat et al. [2010]. The switches between the initiation and progression phases are defined so that

$$k = \begin{cases} 0, & \text{if } c_{i,t} = 0 \\ 1, & \text{if } c_{i,t} > 0 \text{ and } c_{i,t} \leq \phi_c \end{cases} \quad (3.3)$$

The unified cracking model provides predictions for both the crack-initiation phase and the progression phase. $\mathcal{V}_{i,t} = \{V_{i,t}^1, V_{i,t}^2, V_{i,t}^3, V_{i,t}^4\}$ denotes a set of explanatory variables consisting of physical and environmental variables of the pavement segments; as well as traffic loading applied during a time step Δt as defined in Table 3.1.

Table 3.1: Definition of explanatory variable vectors within the pavement cracking models

Category	meaning
$V_{i,t}^1$	Pavement underlying-layer thickness variables
$V_{i,t}^2$	Pavement surface layer thickness variables
$V_{i,t}^3$	Environmental effects variables
$V_{i,t}^4$	Traffic loading variables

$\mathcal{B}_k = \{b_1, b_2, \dots, b_m\}_k$ denotes a set of model parameters. As described in Madanat et al. [2010], for the crack progression model, the parameters were estimated using Ordinary Least Squares (OLS) regression procedures. The crack initiation model parameters were estimated using the *Cox Model*, a stochastic duration model [Nakat and Madanat, 2008], which generates semi-parametric survival functions as shown in Equation 3.4.

For every segment i , the survival function is given as;

$$\begin{aligned} S(l) &= [S_0(l)]^{\Phi(x)}, \text{ where } \Phi(x) = e^{V'B_0} \\ S(l) &= 1 - F(l) \end{aligned} \quad (3.4)$$

Where, l is the cumulative traffic loading since application of new overlay. $S_0(l)$ is the baseline survival function obtained when $\Phi(x) = 1$, where the subscripts have been eliminated to simplify the notation. $F(l)$ is the crack initiation cumulative distribution function (CDF). V represents a vector of variables for a pavement segment, and B_0 is a vector of crack initiation parameters.

The crack progression model is defined as;

$$\Delta C_t = \mathbf{V}B_1 + W_t \quad (3.5)$$

$$C_t = C_{t-1} + \Delta C_t \quad (3.6)$$

where, $W_t = \{w_{1,t}, w_{2,t}, \dots, w_{n,t}\}$; here, $w_{i,t}$ is a random variable describing the model prediction error for a change in cracking level for pavement i in time step Δt . ΔC_t is a vector of increments in the cracking level of the pavement segments. \mathbf{V} represents a matrix of explanatory variables, and B_1 represents a vector of parameters for crack progression.

Therefore, the combined model is formulated as:

$$C_t = k(C_{t-1} + \Delta C_t) + (1 - k)C_0 \quad (3.7)$$

$$C_0 = \begin{cases} z_c, & \text{if } \Pr(\text{Cr}_t) > S(t) \\ 0, & \text{otherwise} \end{cases}$$

where $k \in \{0, 1\}$, $t \in \mathcal{T}$, $\Pr(\text{Cr}_t)$ is the simulated probability of cracking at period t and $S(t)$ is the survival probability at period t obtained from the initiation model, z_c is the minimum detectable cracking level.

Across time steps, the transitions from \mathbf{V}_{t-1} to \mathbf{V}_t and $B_{t-1,k}$ to $B_{t,k}$ are defined by the transition functions described in Equations 3.8 - 3.13.

Variables change from one time period to the other depending on the type of variable, its previous value, and the action taken on the pavement segment. The *subscript zero* in the following equations 3.8 - 3.12 represents the initial state of the pavements and the *superscripts* represent the pavement explanatory variable category as defined in Table 3.1.

$$V_{i,t} = h_V(V_{i,t-1}, a_{i,t-1}) \quad (3.8)$$

$$V_{i,t}^1 = \begin{cases} V_{i,t-1}^1, & \text{if } t > 0 \\ \hat{V}_{i,0}^1, & \text{if } t = 0 \end{cases} \quad (3.9)$$

$$V_{i,t}^2 = \begin{cases} V_{i,t-1}^2, & \text{if } t > 0 \text{ and } a_{i,t-1} = 0 \\ V_{i,t-1}^2 + \Delta V_i^2, & \text{if } t > 0 \text{ and } a_{i,t-1} = 1 \\ \hat{V}_{i,0}^2, & \text{if } t = 0 \end{cases} \quad (3.10)$$

$$V_{i,t}^3 = \begin{cases} V_{i,t-1}^3 + \Delta V_i^3, & \text{if } t > 0 \\ \hat{V}_{i,0}^3, & \text{if } t = 0 \end{cases} \quad (3.11)$$

$$V_{i,t}^4 = \begin{cases} V_{i,t-1}^4 + \Delta V_i^4, & \text{if } t > 0 \text{ and } a_{i,t-1} = 0 \\ \hat{V}_{i,0}^4, & \text{if } t > 0 \text{ and } a_{i,t-1} = 1 \\ 0, & \text{if } t = 0 \end{cases} \quad (3.12)$$

In Equations 3.9 to 3.12, ΔV_i^y (where $y \in \{1, 2, 3, 4\}$) represents the predicted changes in the respective variables from one time step to another.

As described in Equation 3.13, the model parameters do not change until an action is applied.

$$\begin{aligned} b_t &= h_B(b_{t-1}, a_{i,t-1}), i \in \mathcal{I} \\ &= \begin{cases} b_{t-1}, & \text{if } a_{i,t-1} = 0 \\ \hat{b}_t, & \text{if } t = 0 \text{ or } a_{i,t-1} = 1 \end{cases} \end{aligned} \quad (3.13)$$

Where, \hat{b}_t is a realization of a vector of model parameters from their respective probability density functions.

The sum of GHG emissions for a population of pavement segments for a given planning period, p is defined as $G_{\mathcal{I},p}$. The summary statistics, $\mathbb{E}[G_{\mathcal{I},p}]$ and $\text{Var}[G_{\mathcal{I},p}]$ are estimated using the Monte Carlo simulation method, where for each sample $j \in \{1, 2, \dots, s\}$ an initial state $\hat{V}_{\mathcal{I},0,j}$ is randomly generated from the probability density function, $f_V(V_{\mathcal{I},0})$. Then, for the pavement population \mathcal{I} with the planning period p , the maintenance actions $A_{\mathcal{I},p,j}$ are determined from the possible degradation paths generated from Equations 3.3-3.13. Approximations of the summary statistics are computed from

$$\mathbb{E}[G_{\mathcal{I},p}] \approx \widehat{\mathbb{E}[G_{\mathcal{I},p}]} = \frac{1}{s} \sum_{j=1}^s G_{\mathcal{I},p,j} \quad (3.14)$$

and

$$\text{Var}[G_{\mathcal{I},p}] \approx \widehat{\text{Var}[G_{\mathcal{I},p}]} = \widehat{\mathbb{E}[G_{\mathcal{I},p}^2]} - (\widehat{\mathbb{E}[G_{\mathcal{I},p}]})^2 \quad (3.15)$$

Figure 3.1 illustrates the procedure through one time step for a single pavement segment, i , showing a summary of the methodology used in the unified model.

At the beginning of every simulation, a cracking threshold policy to be analyzed is set. While estimating costs, average prices for gasoline and diesel, in addition to the discount rate, are included among the input parameters in the model framework. The procedure is repeated for different values of cracking thresholds to obtain the corresponding expected total emissions and costs. At the end of the simulation, pairs of values for cracking threshold and expected total emissions/costs are obtained.

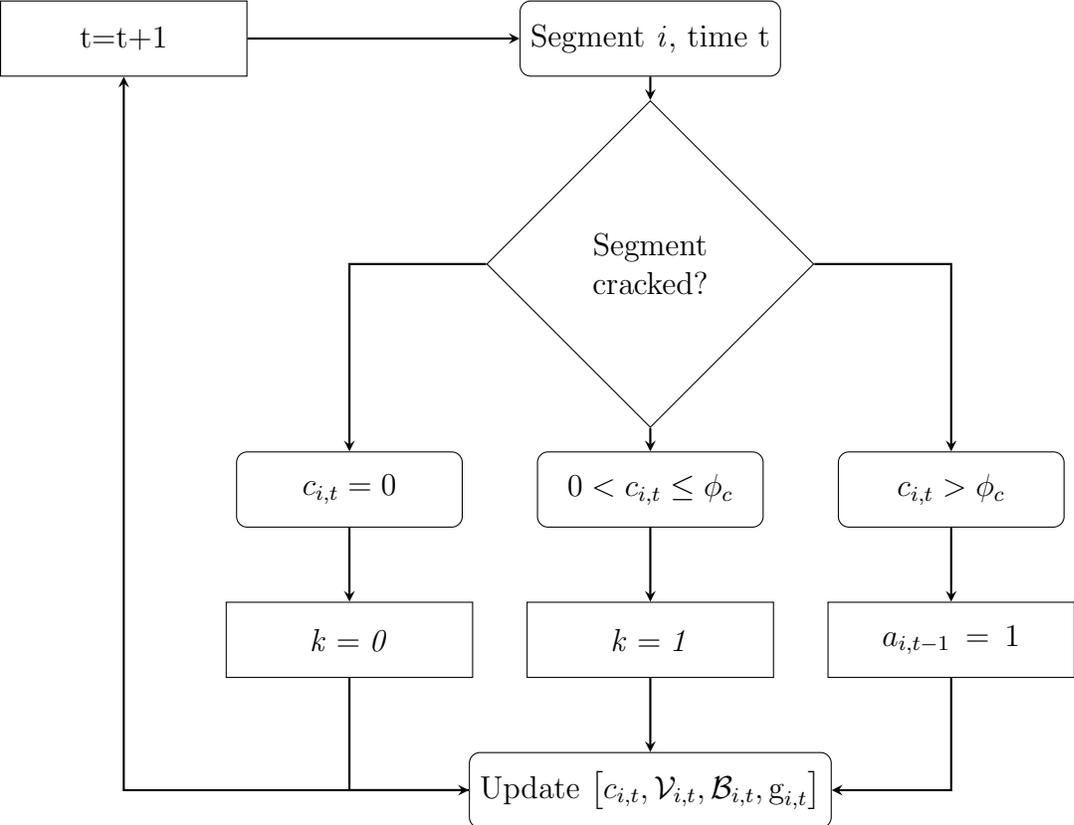


Figure 3.1: Illustration of the simulation process for a given pavement segment through one time period. The crack-initiation model is applied on a crack-free pavement segment. However, if cracking has initiated but has not reached the cracking threshold, ϕ_c , the crack progression model is applied. On reaching the cracking threshold, an overlay action will be triggered which will simultaneously compute the resulting emissions and costs.

Chapter 4

Case Study

4.1 Introduction

A case study was carried out using Washington State DOT (WSDOT) data. This dataset was selected due to the completeness (it contains all the relevant variables) and the large number of observations. WSDOT is one of the first agencies in the United States to fully develop and implement a pavement management system [SHPT]. WSDOT has collected data for the past two decades with all the required distress variables such that it allowed the development of several distress models, including the crack initiation and progression models applied in this research.

WSDOT has over 32,000 lane-km of roadway under its jurisdiction, which is 9 percent of the total roadway miles in the state [SML, 2010]. The others are managed by municipalities, counties, and federal agencies. There are three basic types of pavements managed by WSDOT and these include asphalt pavement, chip seal, and concrete pavement. The following analysis considers only asphalt pavements, which constitute about 55% of the total lane-miles. A planning horizon of $p = 10$ years was selected, which is also the long-term planning horizon for pavement preservation used by WSDOT.

WSDOT uses cracking as the distress that triggers rehabilitation [SML, 2010]. This is because roughness tends to be a lagging indicator that appears later when road distresses such as cracking, rutting, and raveling are not treated on time. Madanat et al. [2010] reported that the cracking threshold for asphalt pavements in Washington State is 10%. This threshold choice is mostly subjective, and this is one of the reasons why Washington State was chosen as a case study with the hope that the results obtained from this research may help steer the agency towards decisions based on economic and environmental considerations.

4.2 Dataset and Monte Carlo Simulation

The dataset used contains $n = 4083$ pavement segments which are randomly selected from the entire segment population of WSDOT pavements, each with a total length of ~ 0.32 km.

There are 15 different variables that can be categorized into three main groups; structural, environmental, and traffic-loading variables. The structural variables include underlying layer thickness, base layer thickness, and the type of material used in the underlying layers. The environmental variables include temperature (both minimum and maximum), precipitation, and number of freeze-thaw days in a year. The traffic-loading category includes the cumulative loading and the annual loading in Equivalent Single Axle Load (ESAL) units.

As described in the joint model framework, the research uses the crack initiation and progression models developed by Nakat and Madanat [2008] and Madanat et al. [2010] (both were developed using the same dataset), to determine the initiation and progression of pavement segments in the sample.

A *Monte Carlo* simulation is used. We make random draws from both the distributions of the explanatory variables (Table 4.1) and the β coefficients (Table 4.2). This is meant to depict the variability in the segment characteristics and external effects over the lifetime of the pavement segment. At the beginning of every simulation, or after application of an overlay to a pavement segment, a realization is selected from the respective distribution of the variables displayed in Table 4.1.

Table 4.1: Variable Population Distributions

Variable	Variable name	Distribution
$c_{i,t}$	Cracking level	$U(\mu - 5, \mu + 5)$
$V_{i,t}^1$	Underlying layer thicknesses	truncated $N(\mu, \sigma = 0.1\mu)$
$V_{i,t}^2$	Surface layer thickness	truncated $N(\mu, \sigma = 0.1\mu)$
$V_{i,t}^{3a}$	Temperature (min, max)	$U(\mu - 5, \mu + 5)$
$V_{i,t}^{3b}$	Precipitation	$U(\mu - 0.1\mu, \mu + 0.1\mu)$
$V_{i,t}^4$	Traffic loading	$N(\mu, \sigma = 0.26\mu)$

In Table 4.1, we indicate that a uniform distribution with bounds of $\pm 5\%$ from the measured value was selected for the cracking-level variable. This uncertainty represents the measurement error. An error of 5% was used because pavement cracks below that number have a tendency to seal up as the asphalt hardens during the early stages of crack initiation.

For the layer thickness variables, a study by Selezneva et al. [2004] found that the distribution of layer thickness measurements is normal, with a mean coefficient of variation for layer thicknesses about 10% for asphalt pavements. Therefore for all the layer thickness variables, a normal distribution was selected. However, a truncated normal distribution was used to eliminate any chances for negative thickness values.

For environmental variables such as precipitation, a uniform distribution was selected which spans a range $\pm 10\%$ of the recorded value which is in agreement with the mean annual precipitation ranges for Washington State [Yang et al., 2010]. The minimum temperature variable is also uniformly distributed, bounded at $\pm 2.8^\circ\text{C}$ from the measured value for the respective pavement segments, which is within the documented limits for temperature variability in Washington State.

Table 4.2: Crack Progression Model Coefficients and Standard Errors (Nakat and Madanat [2008]) used to predict the change in cracking for segment i at time t , $\Delta c_{i,t}$

Variable	β	$\sigma_{se}(\beta)$
Constant	1.18E+00	3.48E-01
$c_{i,(t-1)}$ (%)	-5.86E-01	1.50E-02
c_i (at previous overlay)(%)	8.07E-02	4.03E-03
AC treated base (feet)	-1.75E-01	3.58E-02
PC treated base (feet)	-1.71E-01	1.92E-02
Untreated base (feet)	-3.57E-02	7.01E-03
Underlying layers (feet)	-1.26E+00	1.44E-01
OverlayAA	-3.78E+00	8.75E-01
OverlayBA	-1.54E+00	2.35E-01
Traffic loading (ESALs)	4.06E-06	8.88E-07
Precipitation (mm)	4.40E-04	4.32E-05
Minimum temperature (deg C)	-5.42E-02	9.44E-03

Note: AC stands for asphalt concrete, PC - Portland cement, OverlayAA and OverlayBA represent an interaction term between the type of material used (AA or BA) and the overlay thickness applied, the traffic loading is in ESALs which stands for equivalent single axle load.

Traffic loading variables were drawn from a normal distribution with means and standard deviations obtained from load measurements on the respective pavement segments. The central limit theorem supports our choice of distribution as daily measurements for the respective independent pavement segments are summed over an entire year to obtain the total traffic loading. The coefficient of variation (COV) used is 26%, which is the average COV of traffic loads for class 9 vehicles in Washington State [Al-Yagout et al., 2005]. Class 9 vehicles are representative of the entire truck population because they are the most common throughout the United States, and they tend to carry a high percentage of the loads on most major roads [FHWA, 2001].

Parameter estimation errors for the crack progression model are normally distributed. Their respective standard errors (σ_{se}) were obtained from the crack progression model regression t-statistics derived using Equation 4.1. They are shown in Table 4.2.

$$t_{\beta} = \frac{\beta - 0}{\sigma_{se}(\beta)}; \text{ whereby } \sigma_{se} = \text{standard error} \quad (4.1)$$

As mentioned above, the crack initiation model was developed using the Cox model, where each pavement segment has its own survival function. For the case study, a baseline crack initiation level of 5% was used. Figure 4.1 shows the baseline survival function, $S_0(t)$ obtained from the dataset. Detailed explanation and discussion are presented in Madanat et al. [2010].

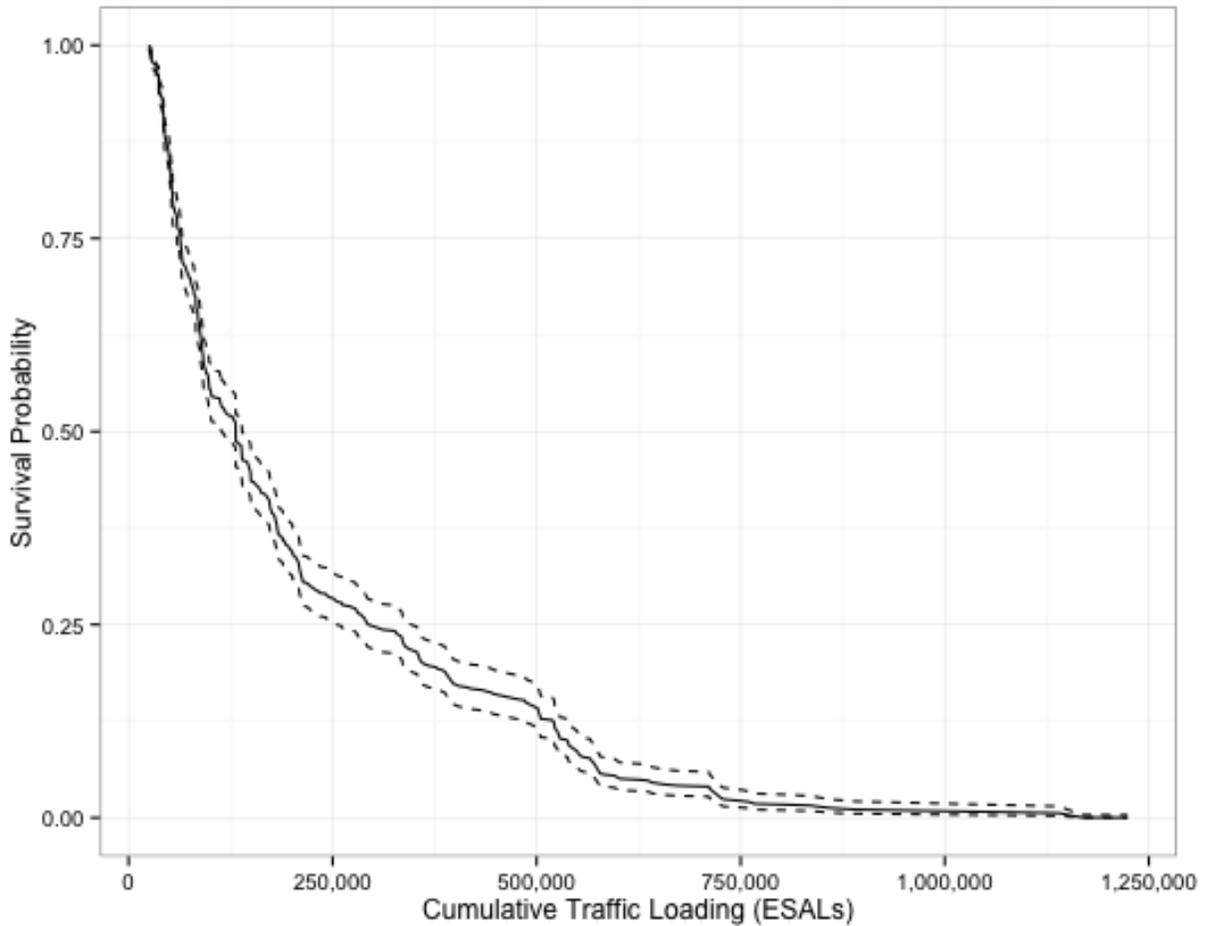


Figure 4.1: Baseline survival function with a 95% confidence interval band around the estimated survival probabilities.

It is important to note that each pavement segment in the dataset has a unique *survival function* whose shape depends on its physical features and external effects. In the crack initiation model, the time variable is the cumulative traffic loading (in ESALs). At every time step, a failure probability $\Pr(c_{i,t} > 0) = 1 - \Pr(\text{Survival})$ is read off from its respective survival curves. To simulate a failure event, random numbers $\hat{r} = \mathcal{U}(0, 1)$ are generated and a pavement segment is said to have cracked if $\Pr(c_{i,t} > 0) \geq \hat{r}$. The crack progression estimation carries on as described in section 3.1, including uncertainty in the independent variables and model coefficients considered, as shown in Tables 4.1 and 4.2.

With the crack initiation and progression models applied as detailed above, the crack-distress evolution of pavement segments was determined. This also enabled the determination of the number of overlays applied on a segment for a planning period of 10 years and the GHG emissions attributed to the maintenance of the respective pavement segments. In

the following subsections, we describe how the costs and GHG emissions for both users and the agency were obtained.

4.3 System-wide cracking threshold policy

Overview

The first part of the case study was carried out with the assumption that a single system-wide policy is applied. A system-wide policy specifies the cracking level at which all the pavements under the jurisdiction of WSDOT are resurfaced. The simulation framework is applied on all the pavement segments in the sample dataset, and the corresponding emissions and costs at each cracking-threshold level are obtained. The results are presented in the subsections below.

Agency emissions

The carbon footprint of an asphalt overlay was calculated using the *PaLATE tool* [Horvath, 2008], and the uncertainty in the value obtained for the emissions per lane-mile was omitted. However, this should not be a concern because the changes in the emissions parameters per overlay action only affect the magnitude of total emissions but not the trend with respect to the various cracking threshold values. If the error term of the overlay emissions parameter is segment specific, given the significant variability in emissions values for pavements as detailed in Santero and Horvath [2009], there might be an effect but not significant enough to alter the results due to the large sample size used.

Aggregating over the entire population of pavement segments allowed the estimation of the total expected GHG emissions for a specific pavement cracking threshold. The maintenance policy (based on the cracking threshold) was varied by unit increments from 6% to 50%. The range starts at 6% because the initializing cracking level was 5% below which a pavement was assumed to be crack-free. The analysis was capped at 50% cracking-threshold because higher values would be unrealistic for WSDOT, which maintains its pavements at lower levels of cracking. The results are shown in Figure 4.4.

Agency costs

The costs to the agency in the simulation were the total of excavation (milling) costs and the asphalt resurfacing costs. The average bid prices for the past 10 years for WSDOT asphalt resurfacing contracts [WSDOT, 2015] were used to determine an estimate for future bid prices using a simple quadratic time series model. The bid prices include the overhead costs that contractors would incur during the asphalt resurfacing activity so the estimated costs are representative of the actual costs. Models for both milling and asphalt placement were used to estimate the future costs. These costs were then discounted to the present value

using the initialized discount rate. From Figure 4.5, we observed the expected trend with

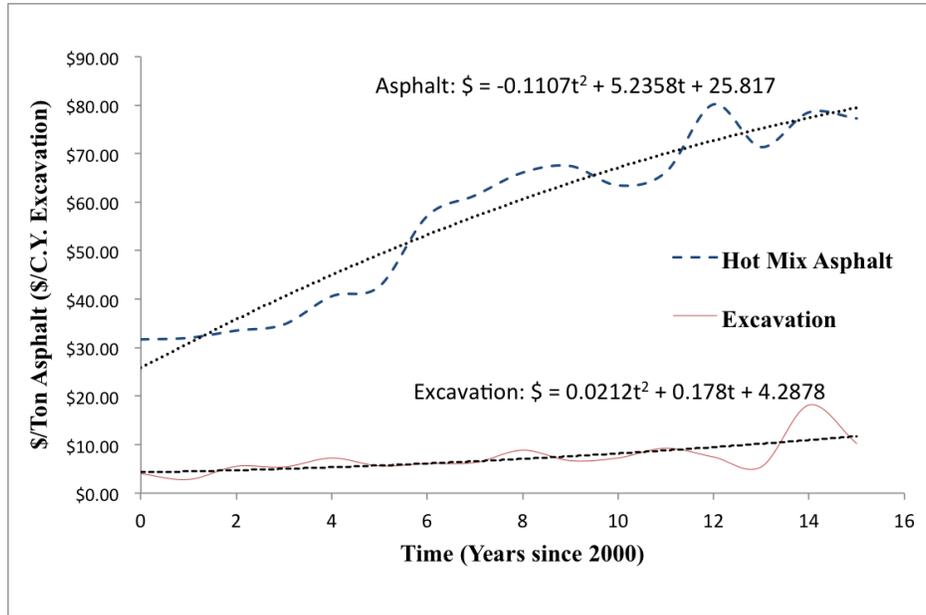


Figure 4.2: Time series plot showing annual changes in costs for asphalt resurfacing and pavement excavation since year 2000.

agency costs decreasing with the increase in cracking-threshold. The important observation, however, was the rate of increase and by what amount the costs would change when the cracking threshold is increased. Figure 4.5 shows that the agency costs decrease by a slightly higher amount than the increase in user costs (for the same range of cracking threshold values), although the user costs are two orders of magnitude larger than the agency costs. Proportionally, the agency costs decrease at a higher rate than the increase in user costs.

User emissions

User emissions contribute a greater proportion of the transportation emissions than resurfacing emissions and understanding their impact on cracking policy change is essential in developing better GHG reduction strategies. Vehicle tail-pipe emissions are the user emissions considered in the analysis and they are obtained as a function of the average annual daily traffic, the proportion of trucks, lane miles, and average fuel consumption rates at the respective cracking distress levels.

The average annual daily traffic (AADT) was assumed to be constant for the respective pavement segments. It should be noted that this does not affect the relationship being estimated in this research as any growth factor applied would increase the corresponding emissions or costs equally at all levels of cracking threshold values. The growth factor could affect the magnitude but not the trend of variation with cracking-threshold policy.

Table 4.3: Regression model relating cracking to roughness

Variable	β	$\sigma_{se}(\beta)$	t-statistic
Constant	8.3552	0.041	205.257
C(IsBridge)	0.8218	0.080	10.227
C(matType1)	0.0599	0.027	2.246
C(matType2)	0.1834	0.049	3.725
C(matType3)	0.7896	0.059	13.278
Alligator cracking	0.0210	0.002	13.881
Longitudinal cracking	0.0078	0.001	7.724
Transverse cracking	0.0322	0.001	24.365
Surface thickness (feet)	-1.2428	0.062	-20.170
Total thickness (feet)	-0.7720	0.021	-36.309
Rutting	12.1292	0.084	143.876

R-squared: 0.117
Adj. R-squared: 0.117

Where matType represents material type for the asphalt concrete layer.
Dependent variable is pavement roughness (IRI)

Cracking influences vehicle fuel consumption through its contribution to roughness. To account for this indirect effect, we developed a relationship between cracking and roughness using the WSDOT database (Table 4.3). This was a regression model for roughness, with cracking as an explanatory variable. We also adopted the relationship between roughness and fuel consumption developed by Zaabar and Chatti [2014]. Together, these two relationships allowed us to relate cracking to fuel consumption.

As the roughness of the pavement increases, fuel consumption increases due to the increase in rolling resistance of the tires. Pavement cracking distress, being a subset of pavement roughness, is expected to have a lower effect on the vehicle fuel efficiency. Therefore an increase in cracking threshold has a lower effect on fuel consumption than a corresponding increase in roughness. The results obtained from the simulations (shown in Figure 4.4 with the shaded region representing a 95% confidence interval band from the mean) indicate that indeed cracking threshold policy has low effect on the fuel efficiency of the vehicles and greenhouse gas emissions. This is in agreement with the literature on vehicle fuel efficiency [DOE, 2016] which show that rolling resistance contributes about 5-7 percent of the vehicle fuel consumption.

The amount of fuel consumed by a motor vehicle over a distance is affected by the efficiency of the vehicle in converting the chemical energy in motor fuel into mechanical energy and transmitting it to the axles to drive the wheels. Figure 4.3 depicts the energy flows and sinks for a conventional gasoline-powered midsize passenger car. Most of the energy available in the fuel tank (about two-thirds) is lost in converting heat into mechanical work at the engine [Menzies, 2006]. While the specific percentages will vary by vehicle type and

trip, the flows shown in Figure 4.3 are generally representative of passenger vehicles today.

For both urban and highway driving, the mechanical energy that goes through the driveline to turn the wheels is consumed by three sinks: aerodynamic drag, rolling resistance, and braking. The energy losses from rolling resistance (for a given vehicle and set of tires) are mainly a function of miles traveled. Only about 12 to 20 percent of the energy originating in the fuel tank is ultimately transmitted through the vehicle's driveline as mechanical energy to turn the wheels. Rolling resistance consumes about one-third of this mechanical energy output.

Rolling resistance, therefore, directly consumes a small portion (4 to 7 percent) of the total energy expended by the vehicle. However, reducing rolling resistance, and thus reducing mechanical energy demand, by a given amount will translate into a larger reduction in total fuel consumption because less fuel energy will need to be sent to the engine in the first place. Also given the higher values of user emissions compared to agency emissions, this increase in fuel losses due to high cracking thresholds though small in proportion to the total, might play a significant role in locating the optimal resurfacing thresholds if the agency's objective is to minimize total GHG emissions.

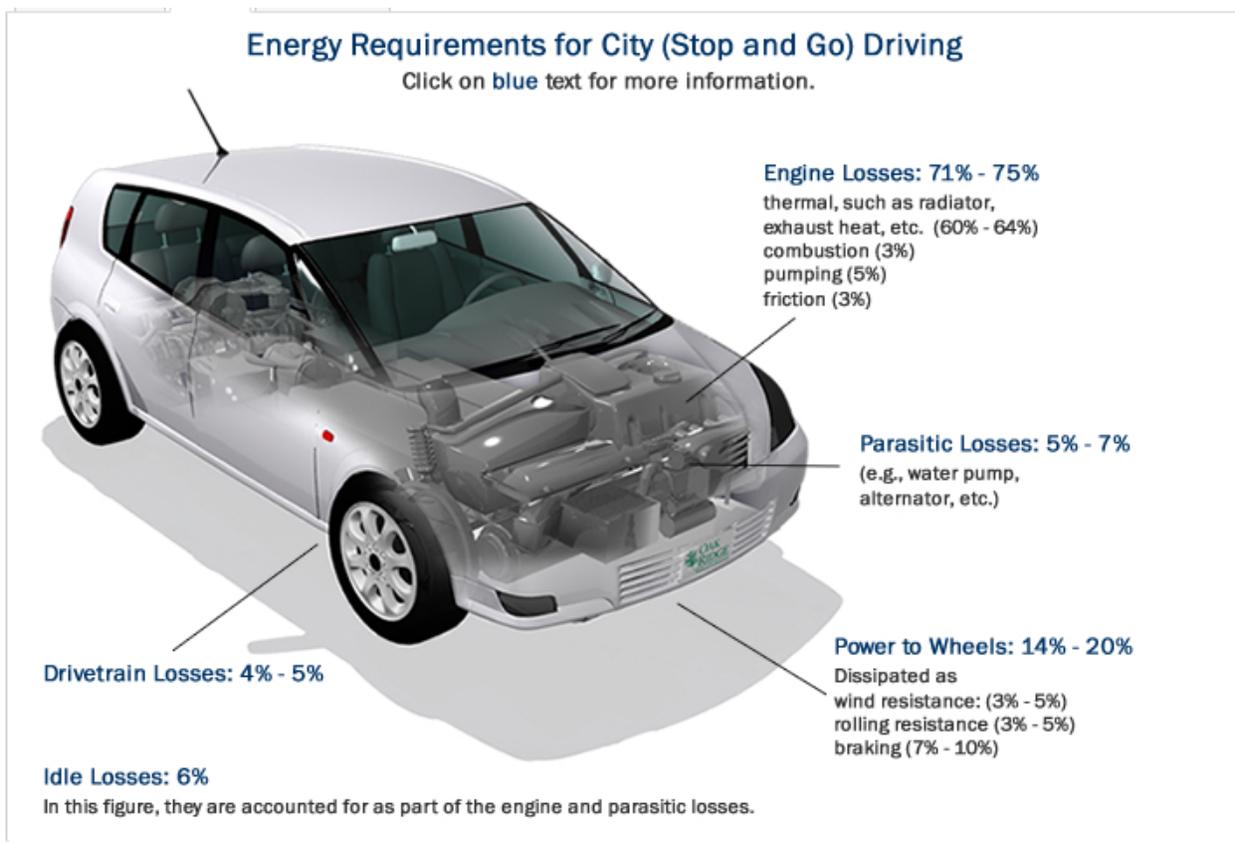


Figure 4.3: Fuel energy losses for gasoline vehicles [DOE, 2016]

User costs

User costs include fuel, tire replacement, and vehicle maintenance costs. The fuel costs were obtained from the forecasted prices for gasoline and diesel. Tire replacement costs were obtained from the tire lifecycle mileage obtained as a function of the vehicle type and distress level provided in the Zaabar and Chatti [2014] paper. After determining the annual vehicle km travelled for trucks and motor vehicles, the tire replacement costs for the vehicles traversing the respective pavement segments were determined.

The vehicle maintenance costs are also a function of the distress level. For each distress level, average lifecycle costs were provided in the Zaabar and Chatti [2014] paper, which were used to determine the annual vehicle repair cost per mile. After obtaining the annual vehicle km traveled, the maintenance costs were determined for both heavy-duty vehicles and passenger cars. A summation of the three cost components provided the user costs at the respective distress level.

In the results displayed in Figure 4.5, we observe that the user costs increase with increased cracking threshold, but the rate of increase is one order of magnitude lower than the rate of decrease of agency costs for the same range of cracking threshold policies. The shaded region represents a 95% confidence interval band from the mean. This suggests that the user costs are less sensitive to the cracking distress levels implying that user costs are less important in determining the agency resurfacing policy when cracking is the trigger distress. Nonetheless, the increase observed can be used to inform policy about the cost-minimizing point for an optimal resurfacing policy, if cost minimization is the objective used for pavement management.

Given the fact that WSDOT uses a policy which overlays asphalt pavement segments at low-levels of cracking, most of the sampled segments used for model calibration had not acquired very high cracking levels, so the model is likely to under-predict the changes in emissions or costs for highly cracked pavements.

Interpretation and Discussion of Results

User costs and emissions are higher than the agency costs and emissions by more than two orders of magnitude. The reason is that the agency activities on a given pavement are spread out over a longer period of time, and resurfacing cycles will seldom exceed two for a planning period of ten years. On the other hand, users travel on the highway continuously throughout the planning horizon. The cumulative effect, even with a small contribution from each individual user, leads to large total emissions and costs.

In order to visualize the trends in both the user and agency emissions, the difference in the emission/cost values between the total for the respective cracking thresholds and the minimum value was obtained and plotted against cracking threshold values as shown in Figure 4.6 and 4.7.

It can be observed that the agency emissions and costs are more sensitive to increasing cracking threshold values than user emissions and costs. The most probable explanation is

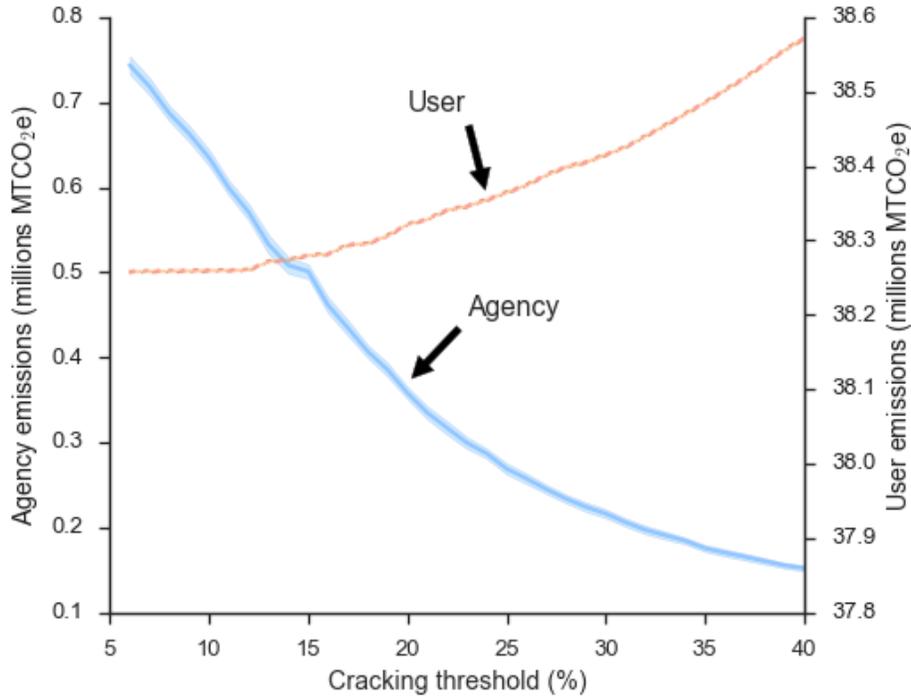


Figure 4.4: Variation of GHG emissions in metric tons of CO₂ equivalents (MTCO₂e) with cracking threshold.

that the agency(resurfacing) activities decrease in number as the agency increases the cracking threshold policy due to the reduction of resurfacing frequency with increasing cracking threshold policy. On the other hand, the total number of users stays the same (assuming zero VMT growth rate) with a moderately low increase in vehicle operating costs (i.e., lower fuel efficiency and higher vehicle maintenance costs) as the cracking threshold increases. This is due to the low effect of the cracking distress on roughness, as roughness was the distress used to model and predict the user emissions and costs in the Monte-Carlo simulation.

From Figure 4.6, we observe a cost-minimizing point at a cracking-threshold value of about 25% and from Figure 4.7, an emission-minimizing cracking threshold of about 27%. Therefore, for the agency to realize both goals of reducing GHG emissions and minimizing resurfacing costs, it should adopt a cracking-threshold policy in the range of 25% to 27%. Given the close proximity of the two optimal values, any of the values within the range will suffice. It is noteworthy that both optimal values are higher than the 10% threshold currently used by WSDOT.

Policy analysis of emission reducing strategies

At high levels of cracking, unintended consequences are likely to be more significant. These factors might include increased incidental stops and/or reductions in speed (due to exces-

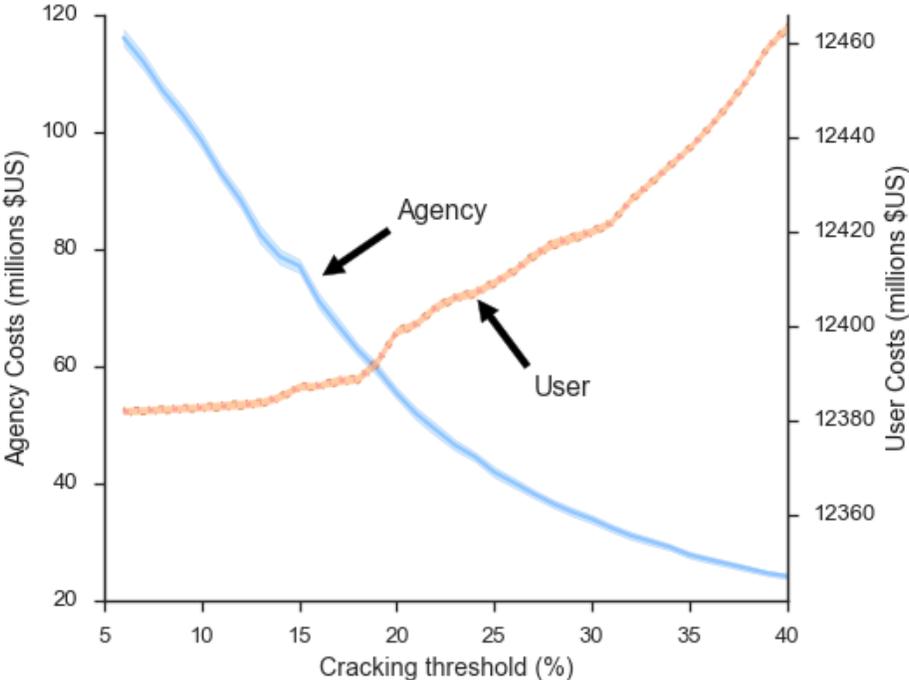


Figure 4.5: Variation of costs with cracking threshold

sive pavement cracking levels), congestion, increased maintenance of vehicles, and increased traffic accidents [Chan et al., 2009]. These incidences lead to reduced vehicle fuel efficiency and, therefore, increased tail-pipe emissions. Likewise, the road users will be affected by other incidences such as increased noise levels on highways, hence increasing the disutility of driving.

The results herein were obtained assuming that the agency considers solely costs and emissions in evaluating their maintenance decisions. However, the agency might not set its resurfacing policy within the optimal range due to fear of unintended consequences which could result from setting the cracking threshold much higher than its current practice. To account for these unquantifiable attributes, an agency might decide to set the cracking threshold to a lower value outside the optimal range. Figure 4.8 displays an illustration for a case where the threshold is 20%. An agency operating at point A and moving to point B can determine the corresponding decrease in emissions due to the cracking-threshold policy change.

Using the difference in Figure 4.8, the change in cracking threshold policy from the current policy used by WSDOT, 10% (A), to 20% (B) will result in an annual GHG emissions reduction of 210,000 MTCO_{2e} after aggregating up to the total lane-miles under the jurisdiction of WSDOT. If applied statewide, the total annual reduction in GHG emissions amounts to 2.3 million MTCO_{2e} given that 9% of the lane miles in Washington State are managed by WSDOT. This is a significant reduction in GHG emissions.

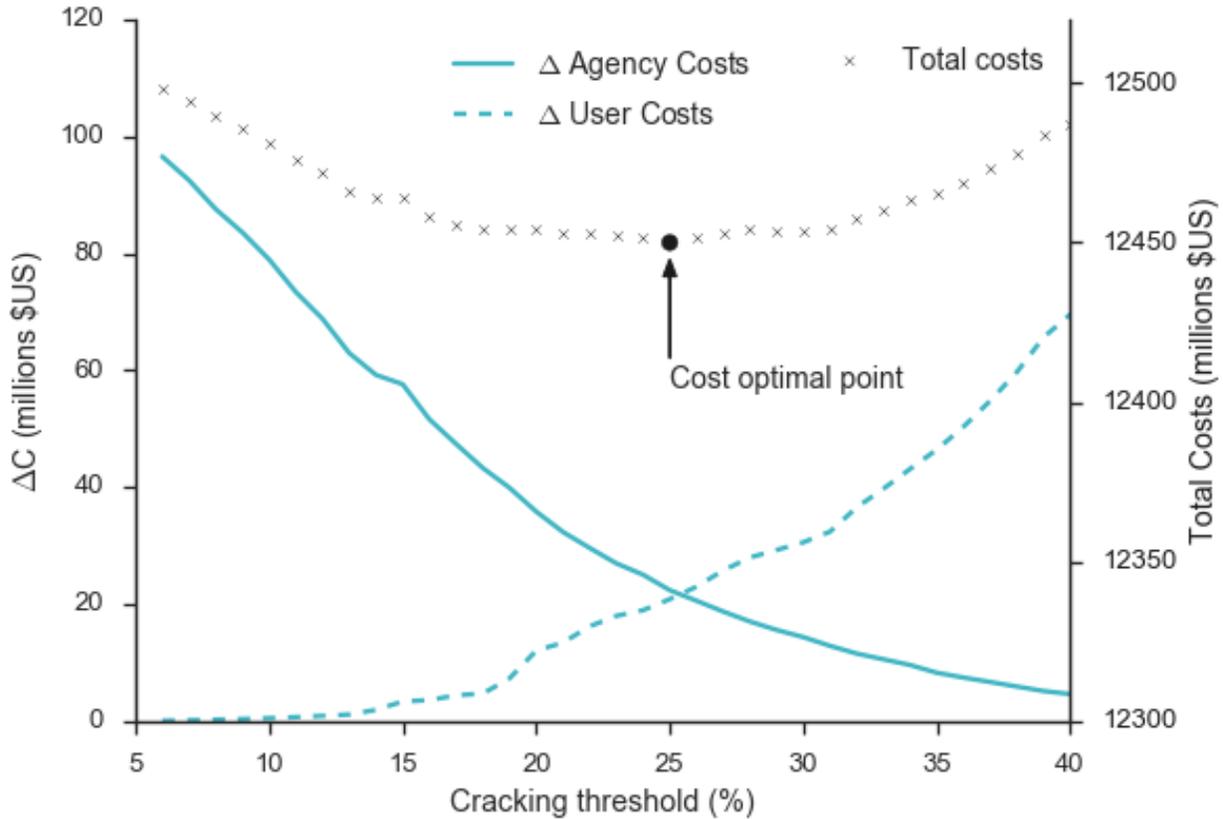


Figure 4.6: Cost optimal cracking threshold.

It is important to note that the reduction in GHG emissions per percentage change in cracking-threshold policy will depend on the point on the curve at which the agency’s current policy lies. Transportation agencies can extract useful information from a curve such as that shown in Figure 4.8 to estimate the benefits or costs of a maintenance policy, as well as compare the policy with other GHG emission reduction strategies such as improving vehicle fuel efficiency.

4.4 Traffic-level segregated policies

Overview

A transportation agency might want to apply different maintenance policies to different road segments categorized by traffic level. Knowing which policies are optimal at the traffic-segregated level is important to efficiently utilize the limited road maintenance funds. In order to evaluate the potential benefits of applying different policies for different classes of roads, we split the dataset into four groups by AADT. The groups were made such that the

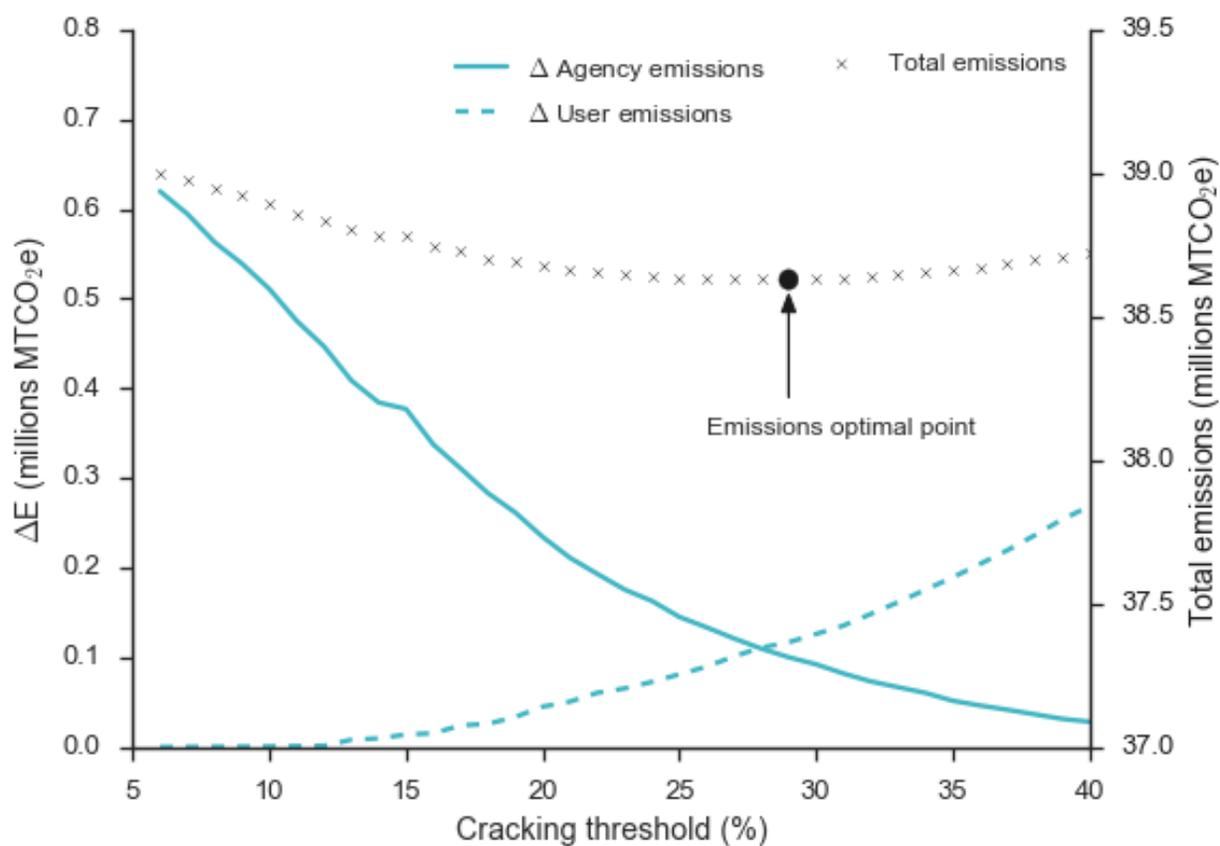


Figure 4.7: Emissions optimal cracking threshold.

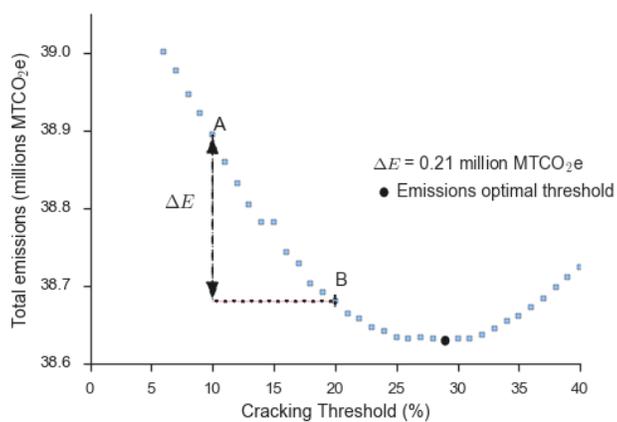


Figure 4.8: Effect of Cracking Threshold Policy Change on GHG emissions.

total lane km in each group was equivalent to 25 percent of the total lane km in the sample dataset, as shown in Table 4.4.

Table 4.4: Traffic volume categorization

Category	Threshold (AADT)
L1	$T \leq 5,000$
L2	$5,000 < T \leq 12,500$
L3	$12,500 < T \leq 27,000$
L4	$T > 27,000$

Description and results

The simulation steps described in section 3.1 were followed, and we obtained the results shown in Figure 4.9. The results show that high traffic volume roads have higher costs and emissions in both the agency and user cases than the low traffic volume roads, because they carry heavier truck loads (measured in ESALs) than the lower traffic volume roads. Given that traffic loading is a key variable in both the crack initiation and progression models, it follows that for roads with higher traffic volume, cracks will initiate and progress to the specified cracking-threshold value much faster than the lower traffic volume roads hence the observed trend. For the users, the costs and emissions are directly proportional to the traffic volume on the respective pavement segments, and we observe a similar trend in Figure 4.9.

Figures 4.10 and 4.11 show how traffic-volume segregated policies and a system-wide policy would impact total costs and emissions. Displayed values are annual emissions/costs aggregated to the entire Washington State DOT asphalt population of pavements. We observe that agency emissions and costs are lower but user emissions and costs are higher using a system-wide policy than those obtained using traffic-level segregated policies combined. We also observe that the differences are small except for the case of user costs. This means that the size of Jensen's inequality is small for both the agency and user emissions, but significant for user costs.

Figure 4.12 shows traffic-level segregated policies considering costs or emissions. The plotted values are differences above the minimum values obtained across all analyzed cracking thresholds for the agency and the users respectively. Traffic-level segregated policies imply different optimal cracking-threshold policies across the respective traffic load classes, which is consistent with the results of Sathaye and Madanat [2012] and Reger et al. [2014] in the case of roughness. The optimal cracking thresholds obtained range from 22% for the low traffic volume roads to 29% for the high traffic volume roads considering both emissions and costs.

The choice between a system-wide policy and traffic-level segregated policies will depend on the goals of the agency. A system-wide policy could be easier to implement. However, if applied at the optimal points, traffic level segregated policies lead to both lower emissions

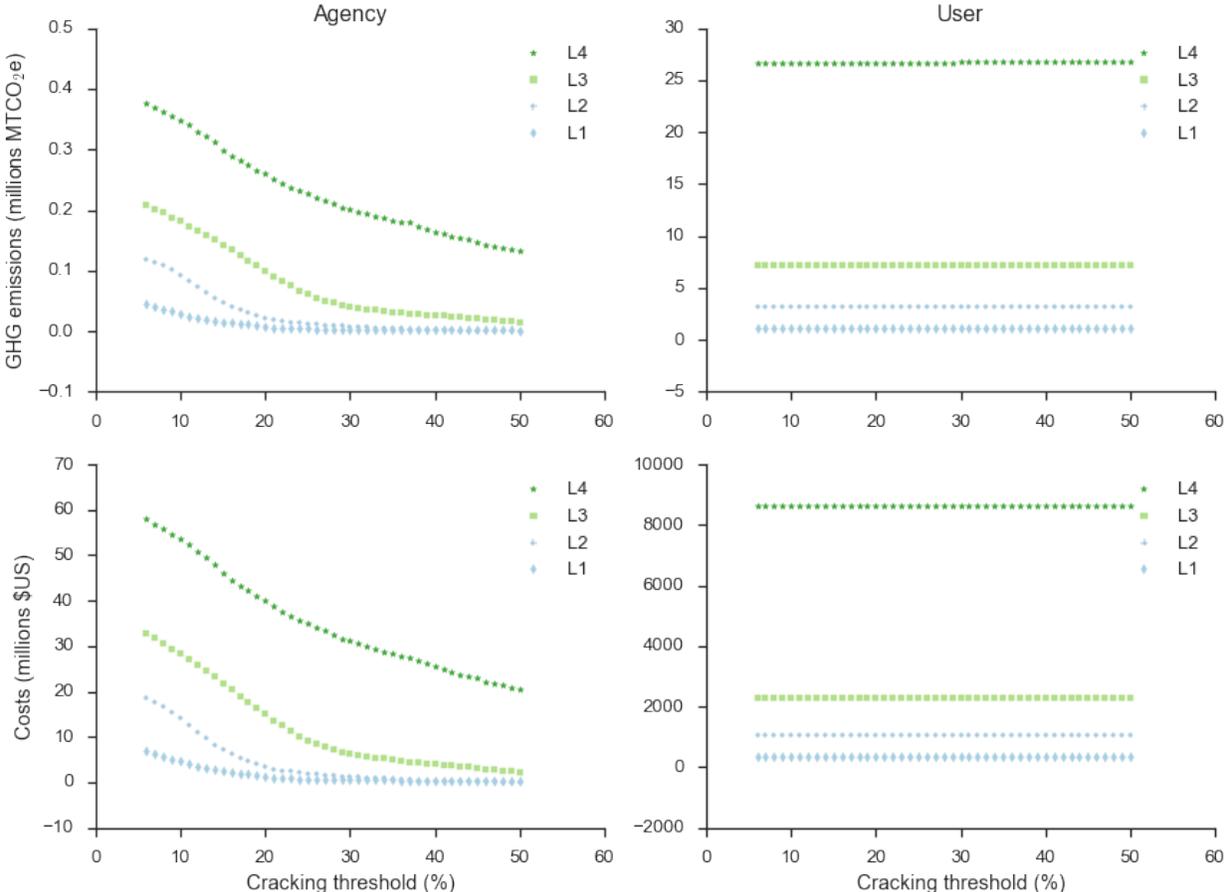


Figure 4.9: Effect of traffic-level specific cracking-threshold resurfacing policies on GHG emissions and costs to both the transportation agency and the road users.

and costs than a system-wide policy. Table 4.5 displays the comparison between traffic level segregated policies at cost optimal points and the system wide cost optimal threshold.

An additional saving of 41,000 MTCO₂e and \$20 million annually was attained with traffic-volume segregated policies, relative to a system-wide policy. If the agency opts to use emissions-optimal threshold instead, the additional savings would be 42,000 MTCO₂e and \$22 million annually for traffic-segregated policies over a system-wide policy. It is clear that the additional savings for using traffic-segregated policies are about the same for the two cases.

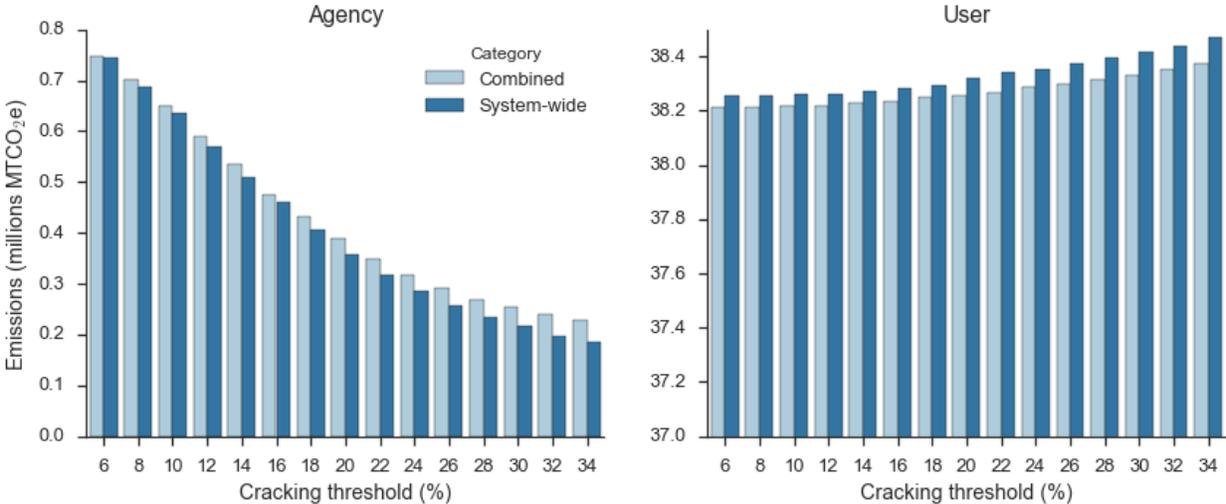


Figure 4.10: Emissions: System-wide cracking threshold policy Vs Traffic-level segregated policies.

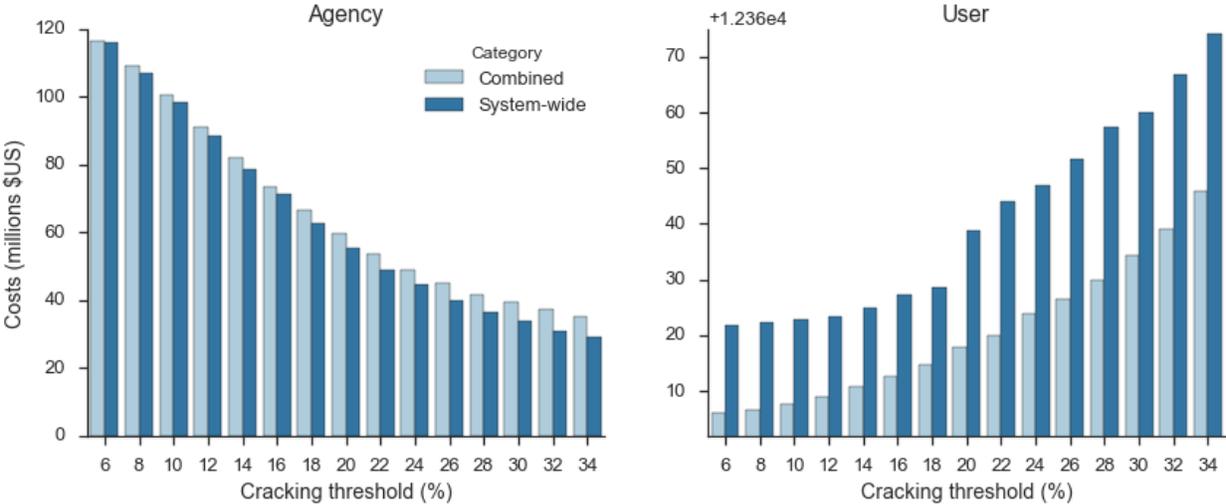


Figure 4.11: Costs: System-wide cracking threshold policy Vs Traffic-level segregated policies.

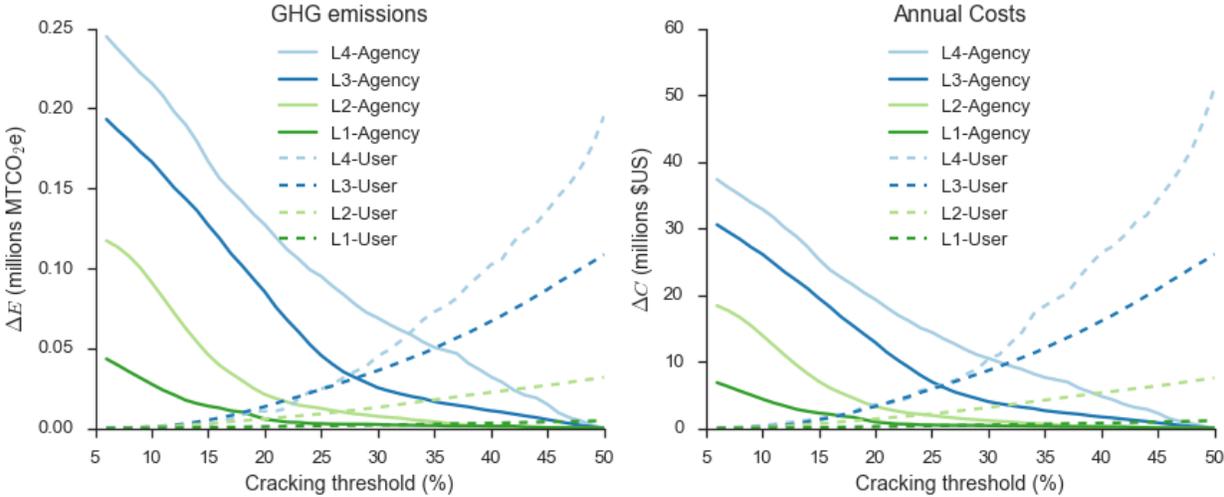


Figure 4.12: Traffic volume level specific cracking-threshold policies while considering costs or emissions respectively. .

Table 4.5: Traffic level segregated cost optimal policies

Traffic Level	Optimal threshold (%)	Total emissions (MMTCO ₂ e)	Total Costs (\$million)
L1	22	1.16	373
L2	23	3.25	1,047
L3	26	7.22	2,326
L4	27	26.96	8,686
Combined		38.592	12,431
System-wide	25	38.633	12,451
Difference		0.041	20

Chapter 5

Discussions and Conclusions

5.1 Contributions

In this research, we showed how cracking-threshold policy changes might affect GHG emissions and costs. With cracking as a trigger distress for rehabilitation, we have shown that an agency-wide cracking threshold does influence the magnitude of future emissions and costs. Inference can be made as to what changes in total expected costs or GHG emissions will accrue to a unit change in cracking-threshold policy, hence allowing for more informed budget allocations.

We have also explored how traffic level segregated policies might differ from system-wide policies. The results show that Jensen's inequality is small for both agency and user emissions, but large for user costs. Traffic-level segregated policies would lead to both lower total costs and emissions than the corresponding values under a system-wide policy. This means that traffic-level segregated policies are preferable for an agency determined to reduce emissions and costs.

5.2 Recommendations for implementation

The initiation and progression models used in the simulation were calibrated using a Washington State DOT dataset, and therefore might not generalize well for other states or countries. In order for the methodology to be applied to other regions, appropriate models need to be developed in order to simulate the local weather and traffic conditions.

In the case study, we observed that traffic-level segregated policies for Washington State were better than a single statewide policy in terms of GHG emissions reduction, as well as total costs. The results show that Jensen's inequality applies especially for user costs. We recommend further investigation of traffic-level specific policies for each state or region to determine which strategy would be optimal for a given state or region.

It is also imperative that a state agency or country implements annual data collection processes that systematically keep a detailed pavement database current. Aside from the

weather attributes, other data that need to be collected include VMT by vehicle type, ESALs (traffic loading), pavement distresses (such as cracking, rutting and roughness), pavement material type, and complete rehabilitation and maintenance history.

In order to obtain good estimates of the GHG emissions from resurfacing activities, it is important to update the global warming potential (GWP) value for pavements, by consistently performing lifecycle assessment whenever new materials are utilized in resurfacing activities. The GWP for pavements may differ by location as there can be a significant contribution from transportation emissions and costs to the life-cycle emissions and costs of the pavement resurfacing activity. A transportation agency should therefore ensure that the emissions values used for a specific state or region correlate well with the location from which the emissions' values were derived in the LCA performed.

Furthermore, the transportation agency should keep an accurate record of the average fuel economy of each vehicle type, and track the fuel prices over time. Keeping such a record makes it easier to calculate the user emissions and costs over time, and these numbers allow comparison with the predicted values. This information can then be used to update and improve the developed model framework, hence providing valuable data which can be used as a basis to evaluate suggested policy changes.

In addition, more specific pavement deterioration models could be easily updated to provide more accurate predictions. The estimated input parameters, for these models, can be updated using a Bayesian algorithm ensuring that the more data collected over time, the more accurate the models and resulting estimates become. Similarly, the cost and GHG emission estimates used in the models could be updated annually based on the vehicle fuel guide by the Environmental Protection Agency (EPA). As technologies change for both users and agencies, the changing costs and emissions could then be automatically incorporated in the database.

Performing the above tasks will greatly reduce the uncertainty associated with the results obtained from developed model framework. The components listed above along with the developed analytical framework are the key components of a PMS that accounts for emissions, as well as comparing several policy alternatives using cracking as the trigger distress.

5.3 Limitations

The developed model framework is adaptable to various roadway segments in terms of traffic level categorization, weather patterns and deterioration rates. It accommodates different fuel economy assumptions, costs, and emissions rates, hence allows for a wide applicability on various pavement segments.

However, the extent to which the framework is generalizable is limited. The analysis carried out does not account for initial pavement capital costs, and the negative effects of highly cracked pavements such as goods damage. The costs of vehicle maintenance and tire costs are accounted for, but not their associated emissions.

Emissions due to traffic delays caused by pavement overlay application were not accounted for since WSDOT typically performs resurfacing activities during nighttime hours when there is low traffic volume in the major metropolitan areas. Lastly, although a distribution of truck types is typically used to estimate the ESALs for pavement deterioration, a representative truck was used to estimate fuel efficiency of the trucks due to absence of truck-type specific volume (or traffic counts) data.

5.4 Future work

The next step for this research could be expanding the definition of agency emissions and costs. During the lifetime of an overlay, the agency normally performs routine maintenance for specific portions of the pavement and incorporating the carbon footprint and costs for routine maintenance allows for a more complete perspective of the total agency emissions and costs in the optimization framework.

Also further studies are warranted in the areas of vehicle fuel efficiency on cracked pavements. A study relating cracking distress directly to vehicle fuel efficiency for all the vehicle categories would allow for better estimates for user emissions and costs.

A study on how vehicle speed might vary for pavements at different cracking levels would also be a great addition to this work, whereby variability in the vehicle speeds could be incorporated in the models to allow for more robust predictions. This study along with studies investigating the effect of vehicle speeds on road accidents could make a great addition to understanding possible unintended costs of a high cracking-threshold policy.

5.5 Conclusion

The analytical framework for optimizing pavement rehabilitation policy developed in this study should be a useful tool for transportation agencies and policy makers who seek to evaluate the effects of the respective cracking-threshold policies on both the agency and the users. Given its current pavement management policy, the agency can estimate the changes in costs and GHG emissions that result from any change in cracking-threshold from the curves obtained from this study. The costs per ton of CO₂e saved can be inferred directly from the estimated changes in costs and emissions, and the agency may choose to select the policy that equilibrates its perceived cost of carbon. If a market of carbon existed, then this analytical framework could define an optimal pavement resurfacing policy that balances life-cycle costs and GHG emissions.

We have observed that the user emissions and costs are always greater than the agency emissions at all levels of cracking threshold policy by over two orders of magnitude. This shows where policy makers should put more emphasis in order to reduce the carbon footprint of the transportation sector. However, we have also observed that resurfacing activities on a pavement have a greater effect on agency emissions and costs than the corresponding

user emissions for especially pavement segments with lower levels of cracking. Therefore, optimizing pavement maintenance activities would almost surely reduce emissions and costs for the agency to a greater extent than for the users.

As a policy measure, it is clear from the results obtained that improved fleet fuel economy will reduce both costs and GHG emissions. On the other hand, investing in more durable pavements leads to slower deterioration and reduces agency costs and agency GHG emissions to a greater extent than user emissions. However, the extent of reduction in total costs and emissions might not be high enough to warrant the extra investment in more durable pavements. For new overlay technologies that reduce both emissions and costs, the associated rehabilitation activity should be explored to leverage the potential of reducing both agency costs and agency GHG emissions at the respective cracking-threshold levels. This is more important in areas such as developing countries where new construction is prevalent.

With the effects of cracking-threshold policies investigated, policy and decision makers have a benchmark from which they can assess potential changes in their pavement management system.

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