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Economically and Environmentally Informed Policies for Road Resurfacing: Tradeoffs between Costs and Greenhouse Gas Emissions

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Economically and Environmentally Informed Policies for Road Resurfacing:

Tradeoffs between Costs and Greenhouse Gas Emissions

by

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Abstract

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Doctor of Philosophy in Engineering – Civil and Environmental Engineering

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As road conditions worsen, users experience an increase in fuel consumption and vehicle wear and tear. This increases the costs incurred by the drivers, and also increases the amount of greenhouse gases that vehicles emit. Pavement condition can be improved through rehabilitation activities (resurfacing) to reduce the effects on users, but these activities also have significant cost and greenhouse gas emission impacts. The objective of pavement management is to minimize total societal (user and agency) costs. However, the environmental impacts associated with the cost-minimizing policy are not currently accounted for. Preliminary research has shown that the optimal policies for minimizing total costs and for minimizing total emissions do not coincide. Instead, there exists a range of potentially optimal decisions, known as the Pareto curve, in which it is not possible to decrease total emissions without increasing total costs and vice versa.

The first part of the dissertation explores these tradeoffs for a system of pavement segments, taking the approach of an agency who looks to minimize their total costs subject to an emissions constraint. This expands on the existing literature where environmental aspects and costs had only been examined at a single facility level. Other pavement management optimization techniques either did not include costs, or did not examine tradeoffs between costs and environmental aspects. For a case study, a network was created from a subset of California's highways using available traffic data. The first step was to look at policies that have been used in practice. Caltrans applies a universal trigger roughness policy, which is a policy where all roads in the network are treated the same. Whenever any road reaches the designated trigger roughness value, it will be rehabilitated, independent of road geometry and traffic. The past policy by Caltrans used a trigger roughness value of 3.5 m/km and the current value is 2.7 m/km. Moving from the past policy to current policy was a good decision, resulting in reductions of 14% and 2.5% for GHG emissions and costs, respectively. Further reductions of 2.5% for emissions and 1.5% for costs could be achieved by switching to one of the optimal policies from our model, where different road sections have different trigger roughness values.

The slope of the tangent of the Pareto curve gives the societal value of carbon at that point. If there is an accepted societal value of carbon, an agency may choose this as the policy to apply.

Alternatively, an agency can use the carbon price as a way to determine feasible emissions reductions targets. If the slope of the curve corresponding to a given emissions constraint was higher than carbon has been valued on the market, the agency may want to reconsider the target. Furthermore, if the emissions target is lower than the emissions minimizing point, the agency can deem the target infeasible without policy change.

Policy changes, such as reducing vehicle kilometers traveled (VKT) or improving construction standards, can shift the Pareto curve. For the case of a reduction in VKT, leaving fewer vehicles on the road lowers the total user emissions and also allows the agency to resurface with less frequency. Agency costs and emissions contribute more to the total than user costs and emissions, so larger reductions in the total can be achieved from changes by the agency. Improved construction standards also lead to lower societal costs and emissions. A reduction in the best achievable roughness by 0.25m/km after resurfacing would reduce total costs by 6.5% and total emissions by 9%. Users would now drive on roads in better condition and the agency would not need to resurface as often since roads in better condition deteriorate more slowly.

The first part of the dissertation does not account for the case where the available budget to the agency is binding. As an alternative approach, in the second part of the dissertation we look at an agency whose main goal is to reduce its carbon footprint while operating under a constrained budget. Literature considering agency budgets had only considered minimizing total costs or maintaining a certain level of condition in the network. A methodology is applied which selects the optimal timing and optimal action from a set of alternatives for each segment while still retaining the Lagrangian dual formulation. This new formulation quantifies GHG emission savings per additional dollar of agency budget spent, which can be used in a cap-and-trade system or to make budget decisions.

We discuss the importance of communication between agencies and their legislature that sets the financial budgets to implement sustainable policies. Using our results, an agency could make a case for needing a certain budget to hit its GHG reduction goals. If it cannot receive any more money for its budget from the legislature, it could sell carbon credits by quantifying the amount of GHG emissions that will be reduced by applying the money they will receive to their rehabilitation budget. We look at the same case study of California roads from the previous section, but now apply this new approach and methodology. We show that it is optimal to apply frequent, thin overlays if the objective is to minimize GHG emissions. This is contrary to the less frequent, thick overlays recommended for minimizing total costs in the literature, but matches what the Washington State Department of Transportation does in practice.

This approach confirms that a universal trigger roughness policy is sub optimal. At every possible budget, there is still a range of optimal trigger roughness values. As agency budgets become lower, the range of optimal trigger roughness widens. This is because it becomes more important to spend the little money they have rehabilitating the segments which will result in the largest reductions. Sensitivity analyses were performed with respect to the fuel consumption due to roughness, deterioration rate, and best achievable roughness level, and the solutions were found to be robust with respect to all three parameters.

Reducing asphalt emissions by using warm mix asphalt (WMA) were found to only be significant when agency budgets are high. However, at those budget values, the cost of carbon to the agency is upwards of $700 per metric ton (mt) of CO_2e, which is significantly higher than carbon has ever been valued on the market. This makes it unlikely that an agency will ever operate at those budget levels, so WMA will not be beneficial for rehabilitation policy. Reductions in asphalt cost see much more significant results, but only when agency budgets are low. A reduction in cost at a low budget effectively gives the agency more money and allows it to rehabilitate more roads where the amount of GHG emissions saved per dollar of agency budget is the highest.

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Acknowledgments

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Chapter 1: Introduction

The United States recently set an ambitious target of reducing net greenhouse gas (GHG) emissions by 26-28% below 2005 levels by 2025 (Whitehouse 2015), and similar goals are being adopted or discussed worldwide. Strong actions have been taken thus far, such as investing in clean power and setting energy and fuel efficiency standards, but more investments are needed. Reducing GHG emissions will require cooperation and willingness from decision-makers across all sectors, especially those with the largest contributions. The transportation sector accounts for 28% of the total GHG emissions in the United States (EPA 2014). However, transportation infrastructure is typically not included in the industry sector, meaning that the overall transportation sector impact may be even higher (Revi 2014). In 2014, there were over 4.8 trillion vehicle-kilometers traveled on 6.3 billion lane-kilometers of roads (FHWA 2014, Census Bureau 2014). The agencies responsible for the care and maintenance of the most traveled roads, state departments of transportation (DOTs), are being compelled to reduce their carbon footprints. This is driven by desire to assist with reaching national targets, public pressure to be more sustainable, and/or state emissions goals set into law (e.g., Assembly Bill 32 in California) (Air Resources Board 2014).

The California Department of Transportation (Caltrans) is an example of a DOT which is compelled to reduce its carbon footprint. One of the specific aspects mentioned in Assembly Bill 32 is the need for cleaner transportation. Since Caltrans is in charge of a system consisting of over 80,000 lane-kilometers of roads, traversed by vehicles driving 283 billion kilometers per year (Caltrans 2011), the potential reductions in emissions with the right strategies are significant (see, e.g., (Sathaye 2010), (Santero 2011), (Santero 2011a), (Santero 2011b)). Caltrans has investigated several strategies for decreasing the emissions in their scope, such as alternative technologies for manufacturing asphalt for roadways, LED lighting of roads, and use of renewable energy in facility operations. However, unexplored opportunities remain (e.g., material selection (Horvath and Hendrickson 1998), local or regional supply chains (Cicas 2007)). In this dissertation, we examine one such opportunity: changing the pavement management system to incorporate GHG emissions. Traditional pavement management systems seek only to minimize life-cycle costs that a road agency and users incur. Environmental impacts stemming from emissions, e.g., of GHGs, have not been previously taken into account.

For managing their pavement assets, agencies have two options for each road segment at any given point in time: they can elect to do nothing, or they can perform a rehabilitation action. If they elect to do nothing, the pavement condition worsens. As pavement condition worsens, fuel consumption and vehicle wear and tear increase, resulting in higher costs and greater emissions from the user vehicles (Watanatada 1987). To keep the user costs and emissions down, agencies can perform a rehabilitation action such as a resurfacing, which improves the condition of the road. While effective in reducing user effects, rehabilitation actions result in large quantities of GHG emissions being released into the atmosphere from producing and transporting the materials, as well as construction (Santero and Horvath 2009). There is an optimal timing to perform an action for each road in the network where the combined user and agency emissions for that segment are minimized. In theory, an agency would always choose to rehabilitate at that timing, but in practice, there are other factors that can interfere. The agency chooses the action and timing, but the total budget they are able to spend is beyond their control. A binding financial budget can force the agency to rehabilitate the roads in the network with less frequency than would be optimal for emissions. For agencies not under a budget constraint (or those using a traditional pavement management system), they may have other objectives such as minimizing total societal costs which need to be considered alongside GHG emissions.

This dissertation describes two approaches that decision makers could take to adopt pavement rehabilitation policies that incorporate GHG emissions. The first seeks to minimize both total costs and GHG emissions for a road network, and the second seeks to minimize total GHG emissions subject to an agency budget constraint. Both result in a range of potentially optimal decisions which are found along the so-called Pareto frontier. Such optimal policies could be adopted by Caltrans or other decision makers in charge of road systems worldwide and can be adapted to include other potential actions, such as reduced vehicle kilometers traveled, to examine their effects on optimal resurfacing policies. The approach that an agency would choose to use depends on their main objective and budget situation.

1.1 Overview

The dissertation outline is as follows: Chapter 2 reviews the existing literature and describes the models and key terms that are used in the study. In Chapter 3, the approach that an agency who is transitioning from a traditional pavement management system to include GHG emissions might take is examined. The formulation minimizes total costs subject to an emissions constraint. A case study of California roads is used to demonstrate the benefits and to compare the current and past policies used by Caltrans. The effects of carbon pricing are discussed, policy implications such as reducing vehicle kilometers traveled (VKT) are considered, and sensitivity analysis is performed. In Chapter 4, we examine an alternate approach where an agency tries to minimize its GHG footprint under a budget constraint. We adjust the methodology to allow for multiple types of rehabilitation activities to create a more realistic model. Again, we perform a case study on a subset of California roads and discuss the effect of budgets on network condition, the possibility of including a cap-and-trade system and sensitivity analysis to show the robustness of the model. Chapter 5 discusses where the results from the two approaches differ and which concepts hold true for both. Chapter 6 presents the conclusions and future work. Appendix A examines the facility level problem.

Chapter 2: Literature Review

The review of existing literature is organized as follows; Section 2.1 describes pavement roughness and why it is used as the measure of pavement condition for this study. Its effects on users, and the actions that an agency can take to reduce roughness are discussed. Section 2.2 describes the costs and GHG emissions associated with rehabilitation actions and how they will be quantified. Section 2.3 explains how the additional costs and emissions from the users due to roughness are modeled. Sections 2.4 and 2.5 describe the equations that can be used to model the progression of roughness over time and the level of roughness after a rehabilitation action is performed. Lastly, Section 2.6 examines the current literature on optimization for infrastructure management.

2.1 Pavement Roughness

Roughness is a characteristic of the surface of a roadway which serves as a description of how uneven the longitudinal profile is in the wheel-path (Paterson 1987). Roughness has an effect on both the structural and the functional aspects of the road and is defined as "the deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage." by the American Society for Testing and Materials (ASTM) Specification E867-82A (ASTM 1982).

The standard measure for roughness is the International Roughness Index (IRI) which is typically measured in m/km or in/mi where an IRI of 0m/km corresponds to a perfectly flat road surface. Some previous measures that were used are the present serviceability index (PSI) and the quarter-car index (QI) (Paterson 1987).

Roughness affects users' perception of ride quality. Beyond a certain threshold, drivers and passengers begin to feel uncomfortable. This threshold was set at 2.7m/km by the Federal Highway Administration (FHWA) and was supported with an empirical analysis by Shafizadeh and Mannering (2003). Caltrans has adopted this same value as its trigger roughness, where trigger roughness corresponds to the IRI value at which a maintenance action should be taken. The HDM-4 model and the WSDOT have adopted 3.5m/km as their trigger roughness (Li 2004). Since the value of 2.7m/km is based upon perceived comfort, it may not be optimal in terms of economic or environmental costs; this reasoning is why some agencies may use a different value and why different values will be examined in this study.

The main strategy that Caltrans employs in order to reduce roughness for a section which has surpassed the trigger value is an asphalt overlay which is a layer of new asphalt that is placed on top of the current section (Caltrans 2012). Caltrans notes that for overlays, the entire roadway must be overlaid to provide a smooth surface. If there is a reason to keep the road surface at its existing elevation, it may also be milled down to a level equivalent to the thickness of the overlay that will be applied. This is commonly referred to as mill-and-fill. These types of resurfacing activities are referred to as pavement rehabilitation. This is distinguished from pavement maintenance, which includes small activities such as crack sealing and patching, and reconstruction, which involves replacing the entire structure.

Note on terminology: Caltrans and the FHWA refer to this phenomenon as smoothness, which may seem as if it should be the opposite of roughness. However, they use the same measurement index (IRI) and refer to the same ASTM specification for their definitions. Therefore, the two terms can be thought of as synonymous, with roughness being used exclusively in this study because this is the terminology used in a majority of the literature.

2.2 Estimating Costs and GHG Emissions Associated with Overlays

State agencies typically have set overlay thicknesses which they apply under given circumstances, for example Caltrans typically applies a 0.25ft HMA overlay when the roughness level is greater than 2.7m/km (Caltrans 2012). Due to this method of application, overlay costs are typically given in dollars per distance. For this study, varying overlay thicknesses will be investigated, so overlay costs will need to be determined in a different manner. Small et al. (1989) calculated costs for overlay application in terms of a lump sum fixed cost and a variable cost based on structural number (which can be converted into thickness of HMA by multiplying by a factor of 0.44), but there were several aspects of the study which do not make it ideal for use. The age of the study is an issue since all of the costs were given in 1982 dollars. Another issue is that there was a "disruption cost" added which was assumed to be 20% of the total project cost. The disruption cost may not be applicable to California roads as most Caltrans maintenance activities are performed at night to try to reduce the effect on traffic. Hand et al. (1999) obtained costs from the New Jersey Department of Transportation (NJDOT) Operations Division which included engineering and construction costs for various overlay thicknesses ranging from 50mm to 125mm and given in dollars per square meter. This study also presented separate costs for mill-and-fill and overlays which is of importance since Caltrans utilizes both types of maintenance activities.

To address the GHG emissions from overlay application, there were three tools investigated: Athena IE, PaLATE and AsPECT. Athena IE is a very comprehensive tool but has not been made universally applicable as of yet; currently it requires specification of a region of Canada. AsPECT uses input energies to determine GHG emissions but has very specific data needs which are not available for this study. PaLATE was chosen as the most appropriate tool based upon the facts that the calculations are visible, enabling the user to follow the process, and that it is based on U.S. pavements. It is acknowledged that PaLATE is not the most current software available, but the values contained can be easily edited in future work.

2.3 Estimating User Costs and GHG Emissions as a Function of Roughness

The cost incurred by the motorists who travel on a given road will increase as the level of roughness increases (Watanatada 1987, Barnes and Langworthy 2004). The effect of roughness on user costs can be split into two parts, non-fuel costs and fuel costs. Watanatada et al. (1987) investigated the effect of roughness on tire wear as well as vehicle depreciation and found it to be significant, however, this study was performed in Brazil in 1982 making its application to current conditions in the U.S. questionable. More recently, Barnes and Langworthy (2004) quantified the per-mile costs of operating an automobile which explicitly accounted for the non-fuel costs related to roughness for the U.S.

Fuel consumption is a function of power output and engine speed (Watanatada 1987). Since an increase in roughness leads to an increase in the rolling resistance that a vehicle has to overcome in order to traverse a given section, there will also be an increase in the power output and engine speed which results in a change in fuel consumption. Watanatada et al. (1987) also examined the effect of roughness on vehicle speed, but the roughness levels that were shown to have an effect are higher than what is likely to be seen in a developed country such as the U.S. There were some sections of the study which did not show an effect of roughness on fuel consumption, but speed was not held constant and the reduction in speed from roughness would improve fuel economy in some cases and offset the additional fuel consumed to overcome roughness. Epps et al. (1999) used data from WesTrack to quantify the effect of roughness on fuel consumption, but the study comprised of only four test vehicles which were heavy trucks traveling at low speeds of 40mi/hr. More recently, Zaabar and Chaati (2010, 2014) calibrated the HDM-4 model to match conditions seen in the U.S. and investigated an array of vehicle types at highway speeds. The study found that the change in fuel consumption was linear with respect to roughness and showed that the HDM-4 model without calibration underestimated the additional fuel consumption due to roughness.

The GHG emissions associated with the roadway users will only take into account the emissions related to the additional burning of fuel, as there has not been a study to quantify the additional emissions from tire wear, maintenance or parts replacement for U.S. conditions.

2.4 Roughness Progression Models

Choosing an appropriate deterioration function is important since the optimal resurfacing strategy is based upon how quickly the pavement is assumed to deteriorate as shown in Lidicker et al. (2013). Tsunokawa and Schofer (1994) assumed the deterioration function was an exponential function based solely upon the current value of roughness, which is mathematically convenient but physically unrealistic. The empirical model from Paterson (1987) is more desirable as it also includes the modified structural number of the pavement (SNC) and the traffic loading, where SNC differs from the standard structural number (SN) because it takes into account the strength added by the sub-grade in addition to the structural layers of the pavement. Paterson (1987) also created a second empirical model which was much more complex. Since roughness is a measure of deviations in the wheel-path, it is inclusive of the other distresses seen in pavements such as cracking, rutting and potholes. This empirical model looks at the incremental changes in roughness due to the changes in these distresses as well as the SNC, traffic loading, maintenance activities performed such as patching, and age of the pavement. To use this model however, it would be necessary to predict the other three distresses as well as predict minor maintenance which puts it beyond the scope of this study. There are many other comprehensive models which have been created as well, but these require specific data which are not available for California (Prozzi and Madanat 2002, Hong and Prozzi 2004, Hand 1999). The first Paterson (1987) empirical model is used for this study, as it is the most comprehensive model that fits within the data limitations.

2.5 Roughness Improvement Models

The resulting roughness value after an overlay is applied is a function of the roughness before application and the thickness of the overlay. The improvement models considered were that of

Tsunokawa and Schofer (1994), Li and Madanat (2002), and Ouyang and Madanat (2004). Ouyang and Madanat (2004) used a model based on empirical data from developing countries. An attempt was made to apply the Ouyang and Madanat model at first in this study, but the resulting thicknesses were found to be infeasible for U.S. conditions. Taking this into account, the Tsunokawa and Schofer model was then utilized and found to provide realistic values for overlay thickness.

2.6 Optimization for Maintenance and Rehabilitation

There are three formulations that can be used to optimize pavement maintenance and rehabilitation; 1) discrete time and discrete state (e.g. Madanat 1993) 2) discrete time and continuous state (e.g. Durango-Cohen 2007) 3) continuous time and continuous state (e.g. Tsunokawa and Schofer 1994).These categories can be further broken up into single or multiple facilities, and the case of multiple facilities can be further divided into top-down (e.g. Golabi 1982) or bottom-up (e.g. Sathaye and Madanat 2012). This research will utilize a continuous time and continuous state formulation for multiple facilities with the bottom-up approach.

Friesz and Fernandez (1979) were the first to study a single facility using the continuous time and continuous state formulation for infrastructure management. They formulated the problem as an optimal control problem but noted that the deterioration curve has a saw-tooth nature where maintenance activities lead to discrete jumps in the state variable and result in computational complexity. The initial paper focused mainly on maintenance and they later solved the problem for highway construction staging but did not solve explicitly for pavement rehabilitation (Fernandez and Friesz 1981). Markow and Balta (1985) were able to solve the optimal control problem for pavement rehabilitation, but the solution only held for a single rehabilitation timing. The issue of the discrete jumps in the state variable was addressed by Tsunokawa and Schofer (1994) through the use of a trend-curve approximation which passes through the center of the spikes in the saw-tooth curve creating a continuous function. The problem was solved using optimal control, by finding an optimal rehabilitation rate, but this approach was later found to be inaccurate (Li and Madanat 2002).

Li and Madanat (2002) were able to solve the problem without the use of optimal control or a trend-curve approximation by using a steady state solution method over an infinite horizon which solves for an optimal trigger roughness instead of a rehabilitation rate. This study showed that steady-state is reached at the time of the first overlay. The optimal policy was found to have a threshold structure where a pavement should be rehabilitated to its maximum achievable roughness level. This result confirmed earlier empirical work (Carnahan 1988, Darter 1985) and was confirmed by later theoretical work (Gu 2012, Ouyang and Madanat 2006). The finite horizon problem was later solved by Ouyang and Madanat (2006) using calculus of variations. Sathaye and Madanat (2011) optimized resurfacing policy over a network using the bottom-up approach and later solved the dual of the problem in order to make the solution applicable to large-scale heterogeneous networks (Sathaye and Madanat 2012).

Multi-objective optimization has been identified as an effective technique for infrastructure management problems (Wu 2012). Network-level Pareto-optimal solutions have been applied to pavement management previously, but have focused on aspects such as cost, performance, condition and work production (Bai 2012, Bai 2015, Fwa 2000, Sathaye and Madanat 2012).

Lidicker et al. (2013) used a multi-objective optimization in which GHG emissions and costs were considered for a single facility and found that there was a tradeoff between costs and GHG emissions resulting in a Pareto Optimal Frontier with each point representing a potentially optimal pavement rehabilitation strategy for that facility that the agency could employ. Zhang et al. (2010a, 2010b) addressed multi-criteria optimization for emissions, energy and costs with respect to the Michigan highway system, but the focus was on a comparison of a new material, engineered cementitious composites (ECC) with asphalt and concrete pavements. Zhang et al. (2013) used life-cycle optimization in order to determine an optimal strategy while taking sustainability factors into account but did not look into the tradeoffs between the costs and these factors or delve into policy implications. Additionally, the work by Zhang et al. (2010a, 2010b, 2013) used discretized deterioration states as opposed to a continuous model. Wang et al. (2012, 2014) came up with an LCA model to evaluate energy and GHG emissions for different rehabilitation strategies and looked at the payback period for agency emissions to be offset by the savings in user emissions, but did not examine costs or delve into tradeoff analysis.

Chapter 3: Minimizing Total Costs Subject to an Emissions Constraint

3.1 Overview

This section describes the methodology for solving a multi-facility, continuous state, continuous time, infinite horizon problem for a heterogeneous pavement network (segments in the network have different characteristics such as traffic loading, structural number and road geometry).

The single-facility problem has been addressed in previous work (Lidicker 2013), but the solution does not extend to system-level optimization. Instead, the methodology described in (Sathaye and Madanat 2012), which efficiently solves the system-level optimization under a budget constraint, was tailored to fit. The agency budget constraint in Sathaye and Madanat was replaced with a yearly budget constraint on total GHG emissions. Further details are explained in the subsequent sections. A substantial portion of the work in this chapter was published in Reger et al. (2014).

3.2 Problem Formulation

The formulation is given by an objective function subject to two constraints. Equation 1, the objective function, is the sum of the annualized costs, V_j, across all facilities in the network, j=1…J. The total costs are inclusive of the agency costs associated with a rehabilitation activity, M_j, and the additional costs experienced by the users due to roughness, U_j. U_j is an integral from 0 to τ. M_j is a linear function of thickness which is based on the one-time cost for the mill-and-fill activity. The total costs are converted to equivalent annualized costs by the factor $\left(\frac{e^r-1}{1-e^{-r\tau_j}}\right)$ (Au and Au 1992), where r is the discount rate and τ_j is the time interval between resurfacings. τ also serves as the decision variable. The first constraint, Eq(2), represents a constraint on the total yearly emissions. The formulation for total emissions is similar to that of total costs inasmuch as it consists of agency emissions from resurfacings, A_j, and additional user emissions stemming from the increase in fuel consumption due to roughness, W_j (costs and emissions associated with the best achievable level of roughness after a resurfacing as well as the aspects of fuel consumption which are unaffected by roughness are beyond the control of the agency and not included in the formulation). It should be noted that in order to annualize emissions, the total is simply divided by τ. This is done because there is no scientific consensus on discounting future emissions (Sedjo and Marland 2003). The other constraint, Equation 3, ensures that the value of τ stays within its upper and lower bounds, τ_j^c and τ_j^e, respectively.

$$\min_{\tau_j} \sum_{j=1}^{J}\{V_j(\tau_j)\} = \sum_{j=1}^{J}[U_j(\tau_j) + M_j(\tau_j)]\left(\frac{e^r-1}{1-e^{-r\tau_j}}\right) \qquad \text{Eq(1)}$$

$$\text{s.t. } \sum_{j=1}^{J}\{Q_j(\tau_j)\} = \sum_{j=1}^{J}[W_j(\tau_j) + A_j(\tau_j)]\left(\frac{1}{\tau_j}\right) \le B \qquad \text{Eq(2)}$$

$$\tau_j \in [\tau_j^e, \tau_j^c] \qquad \text{Eq(3)}$$

The cost models were taken from Ouyang and Madanat (2004). The agency costs, shown in Equation 4, consist of a variable cost based upon the intensity (thickness) of resurfacing and a fixed cost independent of the intensity. The fixed cost consists of elements such as equipment mobilization and design fees while the variable costs represent equipment operation and the purchasing of materials. m_j and n_j are characteristics of the roadway and are based upon the number of lanes and whether the section is urban or rural. The thickness of the overlay, *wj*, needed to rehabilitate the pavement to its best achievable level is given in Equation 5.

$$M_j = m_j w_j + n_j \qquad \text{Eq(4)}$$

$$w_j = \left[\frac{(1-g_2)s_j^-(\tau_j)-s_j^+-g_3}{g_1}\right]^2 \qquad \text{Eq(5)}$$

Equation 6 gives the user cost equation, which differs from Ouyang and Madanat 2004 in that it only includes additional user costs due to roughness. It is assumed that there is a best achievable level of roughness after resurfacing, s_j^+, which is a technological constraint beyond the control of the agency. The user costs from s_j^+ are constant and cannot be affected by policy, so they are subtracted from the total user costs. t represents the time since the last resurfacing. $F_j(t, s_j^+)$ is the deterioration function which gives the condition of the pavement at time, t. The formula for the discounted infinite-horizon user costs is shown in Equation 7.

$$C_j(t) = c_j(t) - c_j(s_j^+) = c_j F_j(t, s_j^+) - c_j(s_j^+) \qquad \text{Eq(6)}$$

$$U_j = \int_0^{\tau_j}\left[[C(t)]e^{-rt}dt\right] = \int_0^{\tau_j}\left[[c_j F(t, s_j^+) - c_j(s_j^+)]e^{-rt}dt\right] \qquad \text{Eq(7)}$$

The deterioration model is taken from (Paterson 1987), and can be found in Equation 8. l_j is a traffic parameter, as measured in 10^6 ESAL/yr, *SNCj* is the modified structural number, and *a*, *b* and *q* are parameters of the deterioration model.

$$F_j(t, s_j^+) = \left[s_j^+ + a l_j t\left[1 + SNC_j\right]^q\right]e^{bt} \qquad \text{Eq(8)}$$

The emissions functions, A_j and E_j, are given in Equation 9 and Equation 10. For agency emissions, there is only a variable part included as the associated emissions due to the fixed components were negligible compared to materials and equipment used in resurfacing. Equation 11 shows the user emissions which are calculated in a similar manner to that of user costs, with the exception being that future emissions are not discounted.

$$A_j = a_j w_j \qquad \text{Eq(9)}$$

$$E_j(t) = e_j(t) - e_j(s_j^+) = e_j F_j(t, s_j^+) - e_j(s_j^+) \qquad \text{Eq(10)}$$

$$W_j = \int_0^{\tau_j}\left[[E(t)]dt\right] = \int_0^{\tau_j}\left[e_j F(t, s_j^+) - e_j(s_j^+)\right] \qquad \text{Eq(11)}$$

3.3 Solution Methodology

This section presents the solution methods which are used to solve the formulation given in the previous section. The formulation is similar to that of (Sathaye and Madanat 2012), with the exception of changing the constraint and decision variable. The Lagrangian dual formulation of the problem is taken here because it is simple to solve since there is only a single dual variable. Additionally, the value for the shadow price directly gives the value for the tradeoff between marginal costs and greenhouse gas emissions. Using this, the policy maker can find out where their organization is operating on the Pareto frontier and deduce how much it would cost per metric ton (mt) to reduce their CO_2e emissions (where CO_2e is carbon dioxide equivalent emissions expressing all GHGs in terms of CO_2). The dual formulation utilizes a common non-linear programming technique and is given in Equation 12 with the constraint given in Equation 13. Λ is the Lagrange multiplier, also commonly referred to as the shadow price.

$$D(\Lambda) = \max_{\Lambda} \left\{ \inf_{\tau} \sum_{j=1}^{J} V_j(\tau) + \Lambda\left[\sum_{j=1}^{J} Q_j(\tau) - B\right] : \tau_j \in \left[\tau_j^e, \tau_j^c\right] \ \forall\, j = 1 \ldots J \right\} \quad \text{Eq(12)}$$

$$s.t. \ \ \Lambda \geq 0 \quad \text{Eq(13)}$$

The first step is to determine the bounds for τ. τ_j^e is the value of τ at which total GHG emissions are minimized. This is done by taking the first derivative of total GHG emissions, W_j, and setting it equal to zero. τ_j^c is the value of τ where total costs are minimized and is solved for by setting the first derivative of total costs, Vj, equal to zero. Next, the solution to the infimum contained within the braces of the dual formulation is solved for, which gives the relationship between Λ and τ as shown in Equation 14.

$$\Lambda = -\frac{dV(\tau)}{d\tau} \Big/ \frac{dQ(\tau)}{d\tau} \quad \text{Eq(14)}$$

Typically, the next step in the solution procedure is to solve the dual sub-problem, taking the derivative of $D(\Lambda)$ with respect to Λ, solving for Λ^*. However, all values of Λ are needed in order to complete the Pareto frontier. With the relationship between Λ and τ known, it is instead possible to choose a selection of values between 0 and infinity for Λ and then solve for the corresponding τ, since at optimality, the value of Λ will be the same for all facilities. There is no closed form solution for calculating τ from Λ, so a simple root-finding method (bisection) is applied which searches for the τ that solves the following equation:

$$-\frac{dV(\tau)}{d\tau} \Big/ \frac{dQ(\tau)}{d\tau} - \Lambda^* = 0 \quad \text{Eq(15)}$$

The total costs and total emissions (which are functions of τ) for each segment at each value of Λ are then calculated. Summing the total costs and total emissions respectively across all segments for each value of Λ creates the Pareto Frontier. A separate solution methodology is not necessary for the single-facility case as it is solved in the same manner as a system-level problem with J=1.

τ was chosen as the decision variable, but either τ or s_j^- can been used since there is a one-to-one mapping between them within the bounds. However, there is no closed form expression for the inverse of s_j^-, which is why it was not used. τ is also more useful for resurfacing planning. It allows for the agencies to know what year facilities will need to be rehabilitated far ahead of time, making adjusting yearly budgets an easier task.

3.4 Case Study

A sample of flexible pavement segments (defined as one km-long stretches) from a subset of Californian highways (representing approximately 1600 lane-km or 3% of the state's entire network) is used to illustrate the benefits of the proposed methodology. The data came from Caltrans' District 4 (one of the 12 districts in the state), which was chosen because it has a variety of pavement segments which include highways that run through major urban areas such as San Francisco and Oakland as well as some rural roads which see little traffic. The assumptions and values for the parameters used in the models discussed in the problem formulation are described in the following sections.

3.4.1 Assumptions

The rehabilitation activity is "mill-and-fill," where the existing asphalt is milled to the exact depth of the new layer. Other minor maintenance activities, such as patching or crack sealing, are assumed to be contained within the deterioration model and are not part of the resurfacing policy. It is assumed that 80% of heavy vehicles will travel in the right lane when there are two or more lanes, as per Caltrans' design standards. Traffic is taken to be constant, with vehicle kilometers traveled (VKT) growth or reduction to be examined in future work. It is assumed that deterioration primarily occurs in the farthest right lane (truck lane) and that maintenance is applied to the entire section when a resurfacing activity is triggered. Alternative cases, such as all lanes deteriorating at the same rate and single-lane resurfacing policies can be found in section 3.6.1.

The Caltrans Traffic Data branch provides information about the average annual daily traffic (AADT), average annual daily truck traffic (AADTT), and the number of equivalent single axle loads (ESAL is the standard measure of traffic load on pavement) per year, but not the structural number (a measure of pavement strength) or number of lanes. However, the number of lanes can be determined by visual inspection using mapping software since the route and cross streets are available as part of the data. The structural number of the pavement can be estimated using the Caltrans design manual since the factors taken into account for pavement design are the number of lanes, AADT, AADTT and number of ESALs (Caltrans 2012).

3.5 Case Study Results

The results for the network-level analysis are shown in Figure 1. Before delving into the benefits of the optimization, the effect of the recent policy change by Caltrans from a trigger roughness of 3.5 m/km to 2.7 m/km was considered. We estimated that the new resurfacing policy saves 3,600 metric tons (mt) CO_2e/yr and \$0.6 million/yr in total costs. This corresponds to an emissions reduction of 14% and a cost reduction of 2.5%. While it is shown that the new policy is a step towards bringing the system closer to optimality, there is still room for improvement. Emissions could be reduced by another 540 mt CO_2e (2.5%) and costs by another $0.3 million (1.5%) if the agency were to move from the 2.7 m/km policy to the cost-minimizing point on the Pareto frontier, which is the point obtained when total costs are minimized without an emissions constraint.

Each point on the Pareto frontier corresponds to a potentially optimal policy consisting of trigger roughness values for each facility. For example, a point close to the cost optimal would have trigger roughness values between the cost- and emissions-optimal values, but more closely resembling the cost optimal. This new approach can be easily adopted into practice since it retains the threshold-based decision-making process currently used by pavement engineers, with the only difference being the need to specify different optimal thresholds for each segment. If an agency is given an emissions budget, it can then determine if that budget is feasible and what the total costs would be in the network with that constraint. To illustrate what happens at a facility level in the network under the proposed optimization, several single facility cases are examined in Appendix A.

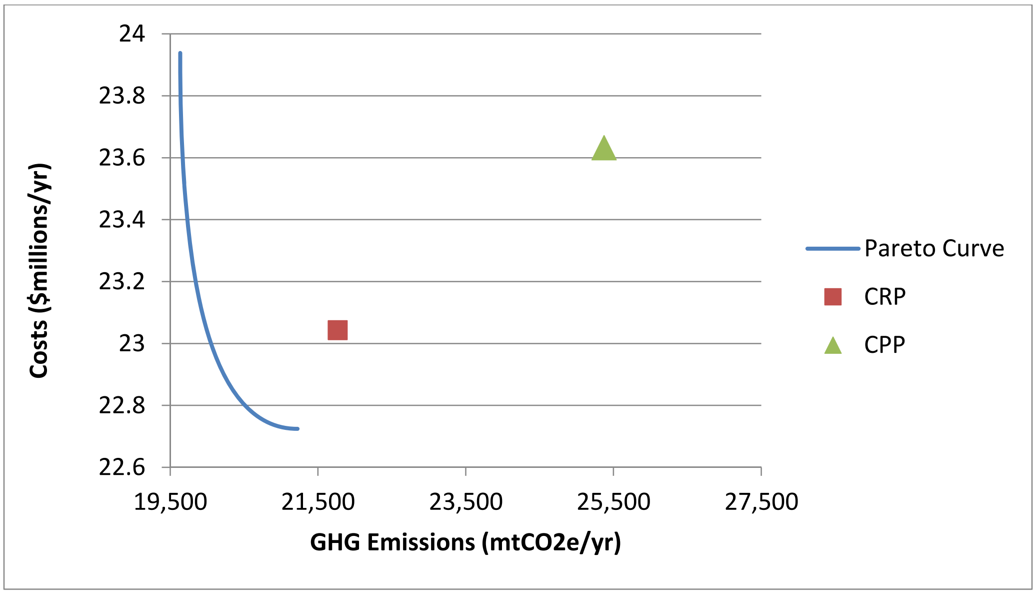

Figure 1: Results comparing the Pareto frontier to the current and past practices applied by Caltrans. (CRP: Caltrans recent policy (trigger roughness of 2.7 m/km). CPP: Caltrans past policy (trigger roughness of 3.5 m/km))

3.5.1 Relationship to Carbon Price

The slope of the Pareto frontier represents the price of CO_2 at that point. Two possible prices for CO_2 are considered (Figure 2): the price of $13.62/mt CO_2e, determined from California's second carbon auction (Environmental 2013), and the price of $110/mt CO_2e, from a study (Knittel 2011). It is possible to make some conclusions about the amount of CO_2e that can be saved by moving from the cost-optimal point to either of those two points. For the California price, although it is very close to the cost optimal point, it would still result in a savings of 50 mt CO_2e/yr (0.2%). The value from (Knittel 2011) would result in a savings of 450 mt CO_2e/yr (2%) since it is located farther from the cost-optimal point on the graph. The savings discussed are only for the subset of Caltrans District 4 roads used in the case study. Scaling up to the entire Caltrans network will lead to higher savings as the case study only accounts for about 3% of the entire network. Looking at carbon price another way, the given emissions budget decides the societal value for carbon. For example, if Caltrans was told they had to reduce their GHG emissions to 20,000 mt CO_2e/yr for the subset of roads discussed in the case study, this would correspond to a CO_2 value of approximately $750/mt CO_2e, which is considerably higher than carbon has ever been valued on the market. This can lead to more informed emissions budgeting. Another extension of the carbon pricing is that it can be used to compare it to the costs of carbon reductions from alternative actions (such as using LEDs in roadway lighting).

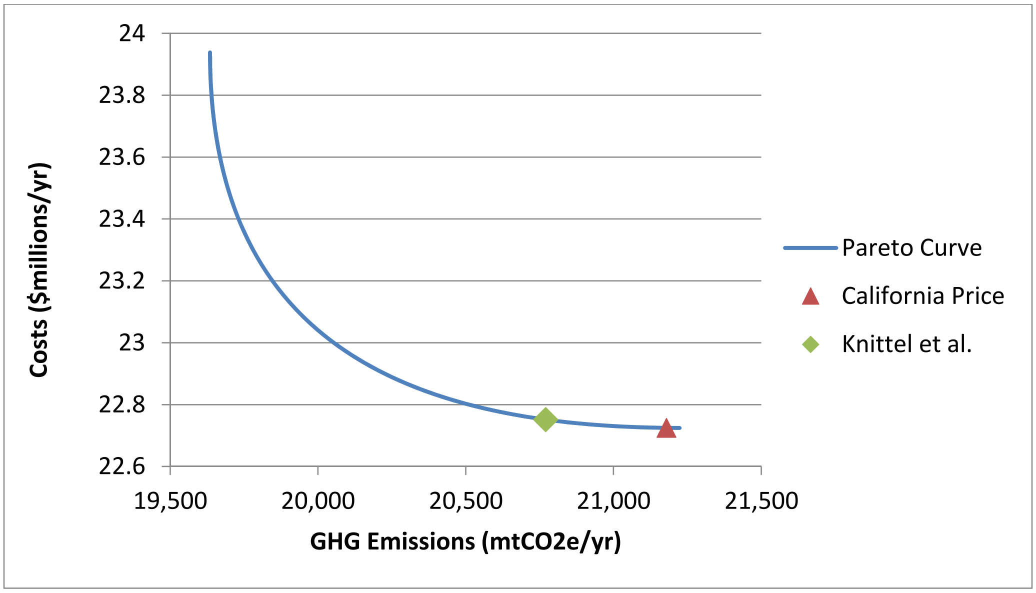

Figure 2: Relation of carbon price to Pareto frontier

3.5.2 User versus Agency Costs

When discussing the idea of increasing costs to reduce emissions, it is important to see who is bearing these additional costs. Figure 3 shows the differentiation between user and agency costs. The cost-optimal point falls on the far right of the frontier, so moving left from there to reduce emissions sees an increase in agency costs accompanied by a decrease in user costs. What this means for agencies is that increasing their annual costs not only has an effect on reducing total emissions, but it is coupled with the benefit of reducing costs to the users. This also gives the agency a quantitative measure of evaluating their budget needs.

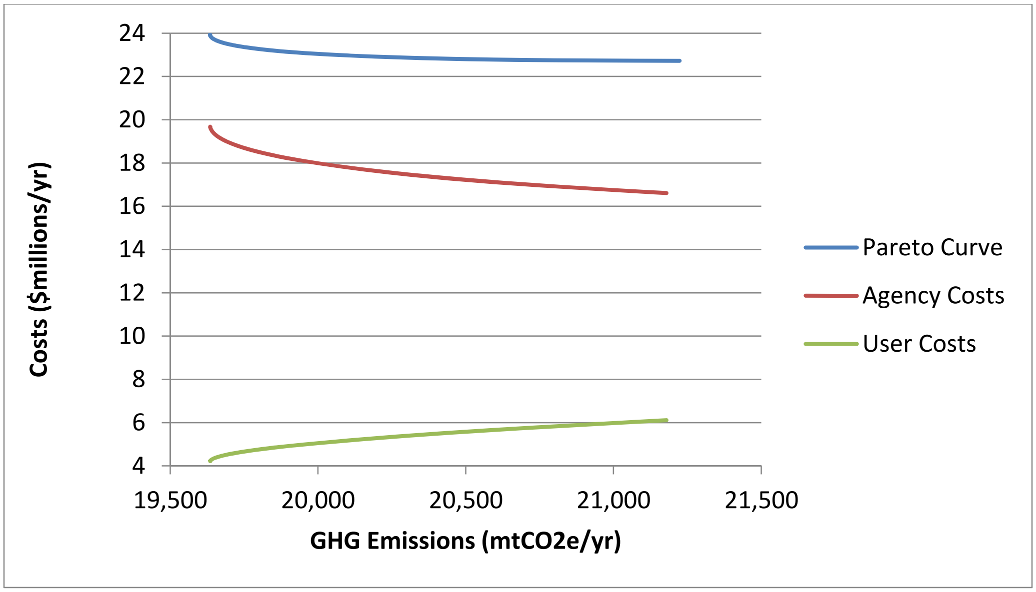

Figure 3: Cost split between users and agency for the Pareto frontier

3.5.3 VKT Reduction (Policy Sensitivity Analysis)

There are some cases in which the agency cannot meet its emissions target from simply moving along the Pareto frontier, regardless of the budget. They would need to consider other policies, such as reducing total VKT. Such action reduces both total emissions and total costs for the network, as shown in Figure 4. A 10% reduction in VKT reduces the yearly costs by about $0.6 million (2.5%) and yearly emissions by 950 mt CO_2e/yr (4.5%). A 20% reduction sees costs reduced by $1.3 million/yr (5%) and emissions by 1,900 mt CO_2e/yr (9%). User costs are expected to drop since there will be fewer travelers on the roads, but agency costs also see a reduction of $0.2 million for 10% VKT reduction and $0.4 million for a 20% VKT drop since the roads need to be resurfaced less frequently. Figure 3 showed that the agency costs contribute more to the total than user costs, which is why a large change in total users may not result in a large change in the total. In the situation where roads are under-designed, a reduction in VKT will be even more significant since it will also slow the deterioration due to reduced truck traffic.

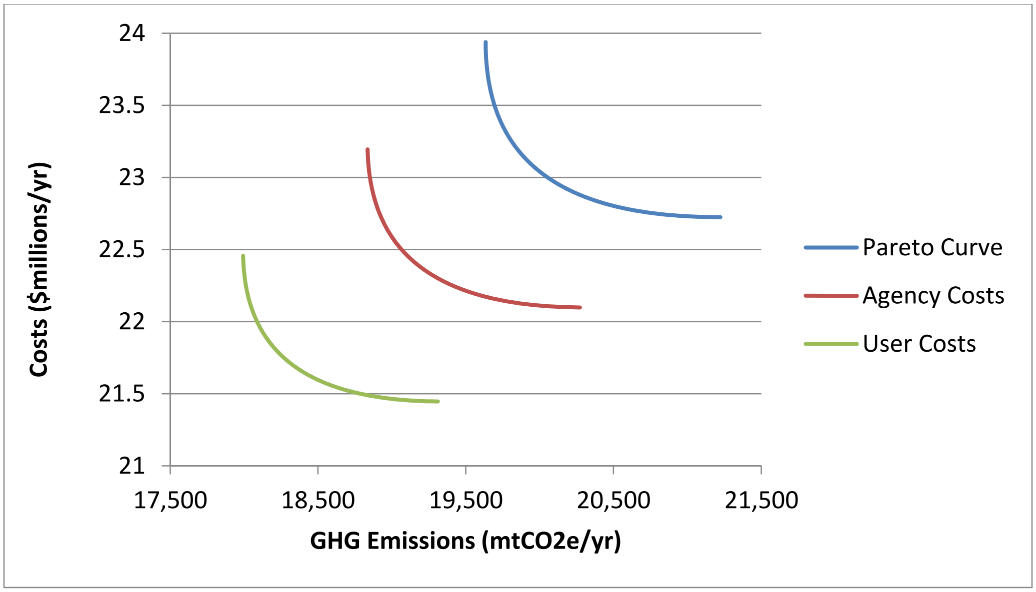

Figure 4: The effect of reducing vehicle kilometers traveled on the Pareto frontier

3.5.4 Improved Construction Standards

Figure 5 shows the effect of changing the best achievable roughness level from 1 m/km to 0.75 m/km. It can be seen that the entire Pareto frontier shifts down and to the left, resulting in significant cost and emissions savings across the network. It was found that this change will benefit both the users and the agency, with each seeing decreases in total costs and total emissions. This stems from the fact that the deterioration equation has a slower rate of change when roughness is lower. By starting at a lower value, the users will travel on better roads for a longer period of time and the agency will not need to repave with as frequently. A possible policy application is for agencies to offer incentives for reaching a better roughness level after a mill-and-fill. For this case study, it was shown that the agency costs would be reduced by $1.5M/yr (6.5%) and the total GHG emissions reduced by 2,000 mt CO_2e/yr (9%) with a best achievable roughness of 0.75 m/km.

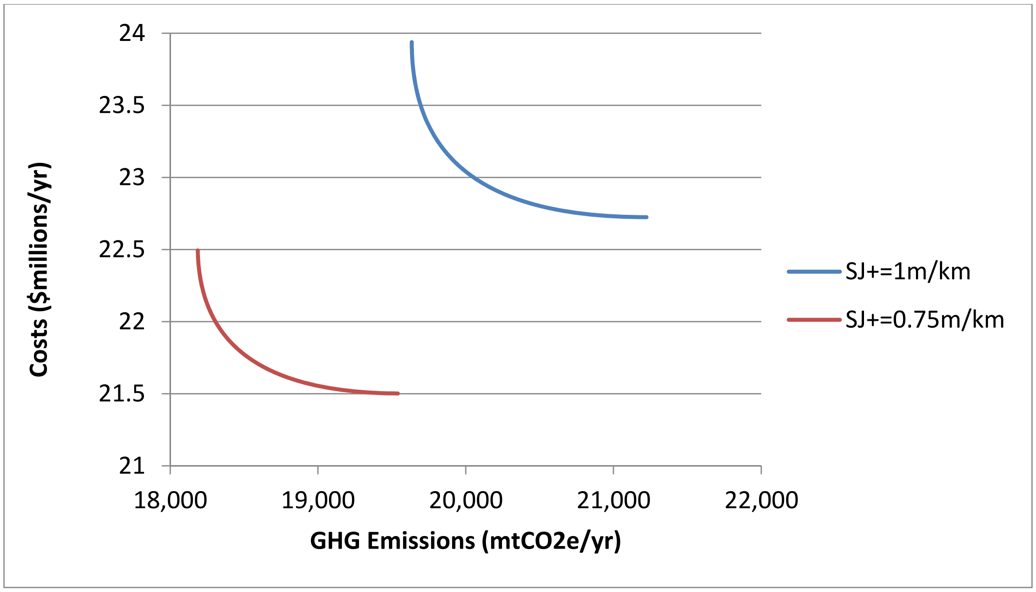

Figure 5: Effect of changing best achievable roughness level

3.6 Uncertainty and Sensitivity Analysis

There are 3 main areas where uncertainty is likely to occur: the rate of deterioration for roughness, the best achievable roughness level after resurfacing, and the amount of traffic on each section. We assume that the agency will use a predetermined policy, where they always apply the action and timing specified by the model. This means that if they are supposed to resurface at an interval of 10 years expecting the roughness to be 3.0 m/km, they will still resurface at 10-year intervals for that section even if the pavement condition is 2.0 m/km or 4.0 m/km at that time. It also means that they will not update the model to reflect changes in traffic volumes.

To represent uncertainty with respect to deterioration rate, we assume that the rate of deterioration given in the Paterson equation is normally distributed with the mean being the assumed value and the standard deviation being 25% of the assumed value. Figure 6 shows the results of the sensitivity analysis for deterioration rate uncertainty. 80% of the simulations resulted in GHG emissions within 500 $mtCO_2e$ of the predicted value from the optimization, so the model is robust with respect to deterioration rate. That said, the expected value is higher than the predicted, so the actual emissions if these policies were to be applied may be higher than the curve displays.

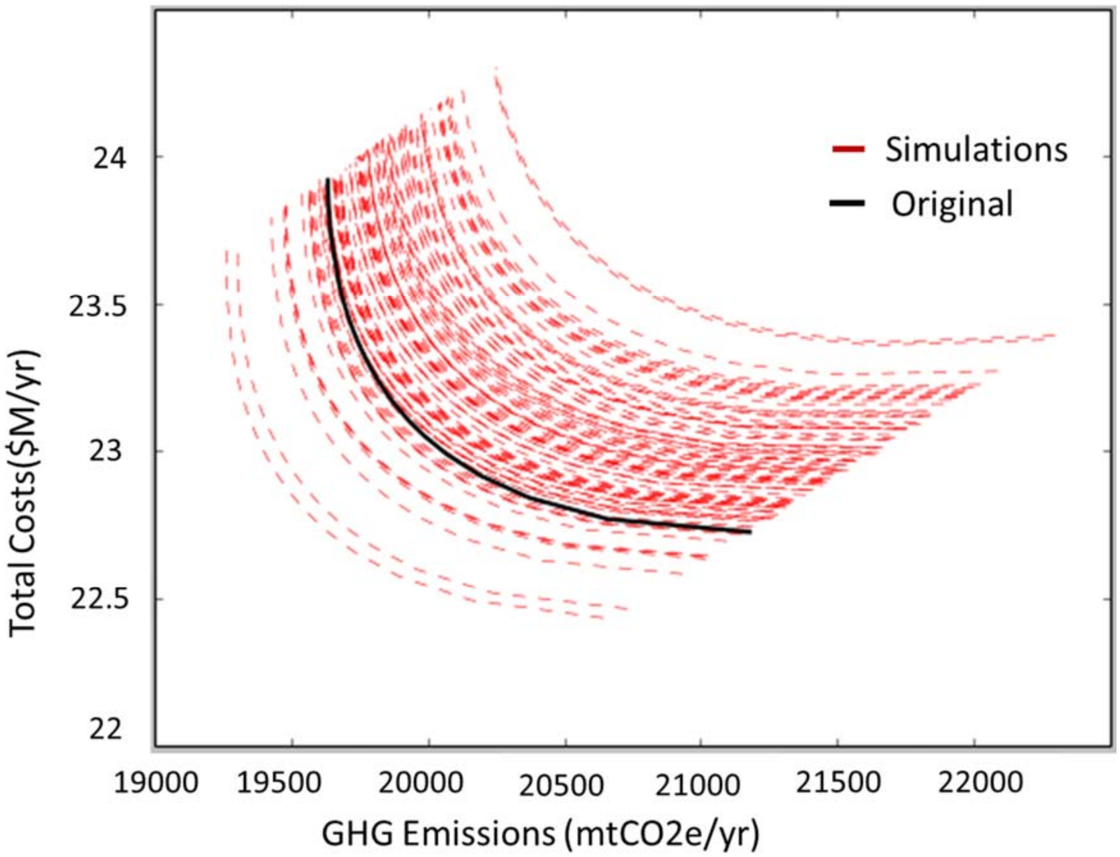

Figure 6: Sensitivity analysis for deterioration rate

The next parameter considered for uncertainty was the best achievable level of roughness after resurfacing. We assume that the best achievable level has a mean of 1m/km (the value assumed in the case study) and a standard deviation of 0.25 m/km. The results, shown in Figure 7, demonstrate that the model is not sensitive to uncertainty in the best achievable roughness level after resurfacing. The average value of the simulations is very close to the predicted value and 95% of the simulations fall within 250 $mtCO_2e/yr$ of the predicted value.

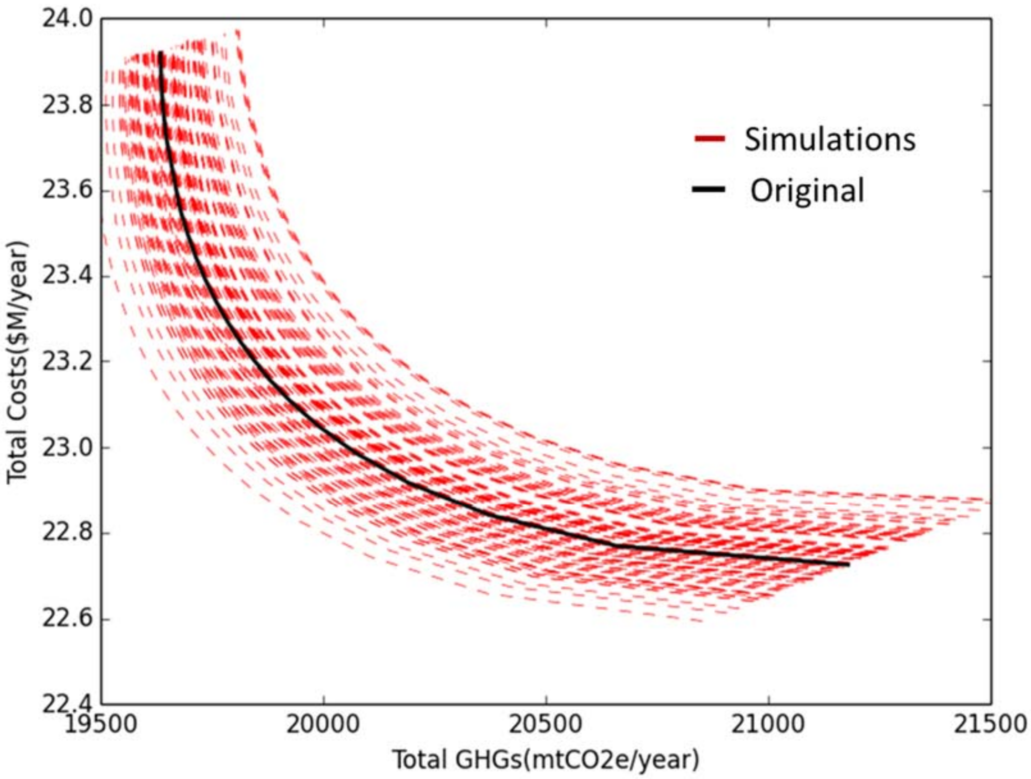

Figure 7: Sensitivity analysis for best-achievable roughness level

The last source of uncertainty considered for this chapter was a possible change in traffic volumes for any of the sections. To address uncertainty with respect to traffic, we assumed that the volume of traffic for each segment is normally distributed with a standard deviation of 25% of the current traffic. Figure 8 shows that traffic changes have little effect as 95% of the simulations fell within 100 $mtCO_2e$ of the predicted value.

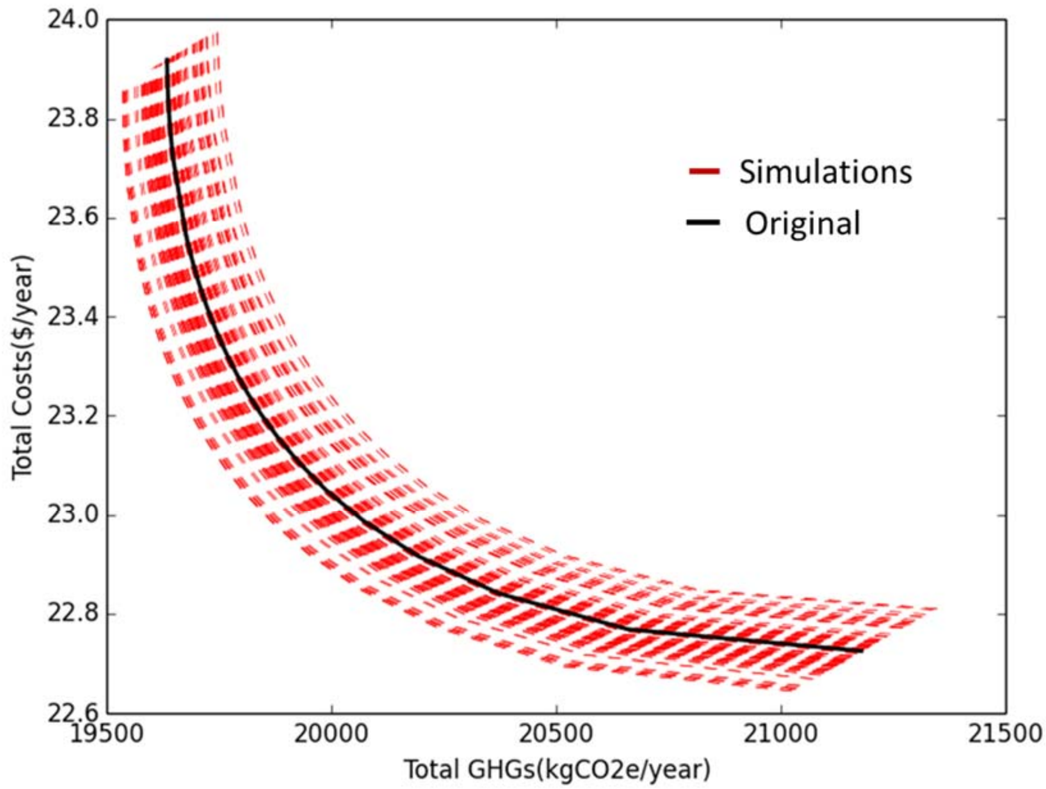

Figure 8: Sensitivity analysis for traffic changes

3.6.1 Alternative Cases for Costs and Deterioration

There are three potential ways to consider the costs and deterioration. The base case is used for the main analysis in the chapter, with the alternative cases described in this section. Alternative Case 1 (AC1) assumes that lanes deteriorate at the same rate and the entire section of the roadway will be overlaid when a maintenance action is taken. This follows the assumption that nearly all of the deterioration will be caused by environmental factors, so the lanes with truck traffic will deteriorate at the same rate as all other lanes. This also assumes that when a resurfacing is applied, it will be applied to the entire roadway section to keep constant elevation in congruence with Caltrans design guidelines (Caltrans 2012).

Alternative Case 2 (AC2) maintains the assumption of deterioration only in the right-most lanes, but also assumes that only the lanes which experience the most deterioration will be rehabilitated. Although less common in application, this may be useful for policy implications since it will only address the lanes that need rehabilitation, preventing the waste of additional funds on rehabilitating lanes which are still in acceptable shape. This results in less new material being used, reducing agency costs and emissions, but may be more difficult to implement in practice. If the construction does not exactly match the elevation, seams may occur between lanes, posing a hazard to motorists.

Figure 9 shows the results of the system level optimization for AC1. The Caltrans current and past policies are considerably farther from the Pareto curve than in the base case. This is because the user costs are now occurring in all the lanes, instead of just the right-most lane. Figure 10 displays the results for AC2. Assuming deterioration only occurs in the right-most lane, switching from a policy where the entire road was overlaid to one where only single lanes were rehabilitated (switching from base case to Alternative Case 2) reduces GHG emissions by 40% while also reducing costs by 60%. For all cases, the change from the past policy (3.5 m/km trigger roughness) to the recent policy (2.7m/km trigger roughness) was shown to be effective in reducing total costs and total emissions, and that further reductions in both costs and emissions can be realized by moving to the policies on the Pareto curve.

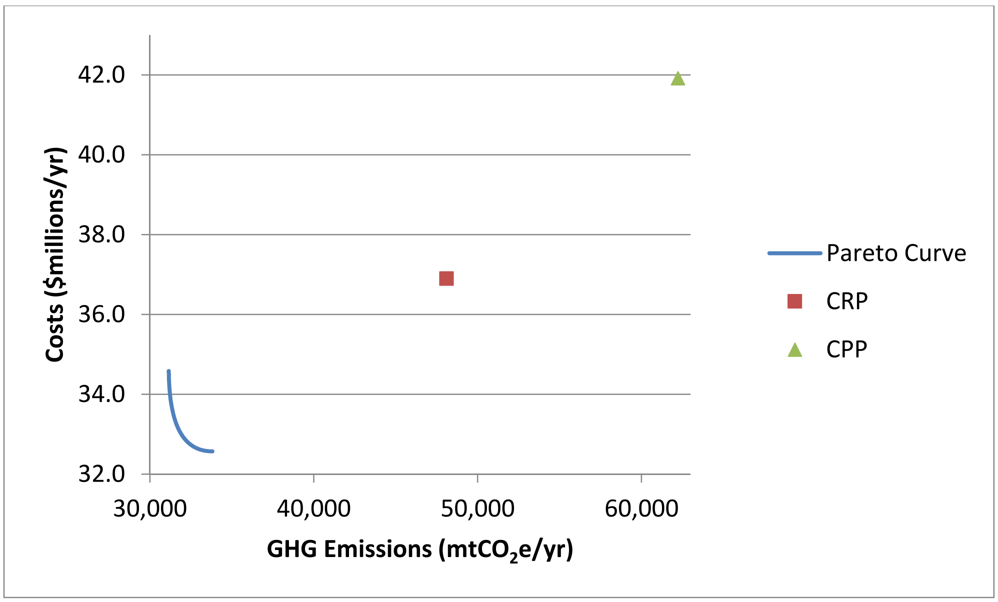

Figure 9: Results comparing the Pareto frontier to the current and past practices applied by Caltrans for Alternative Case 1 (deterioration occurs in all lanes and the entire roadway is resurfaced when one lane surpasses the trigger roughness)

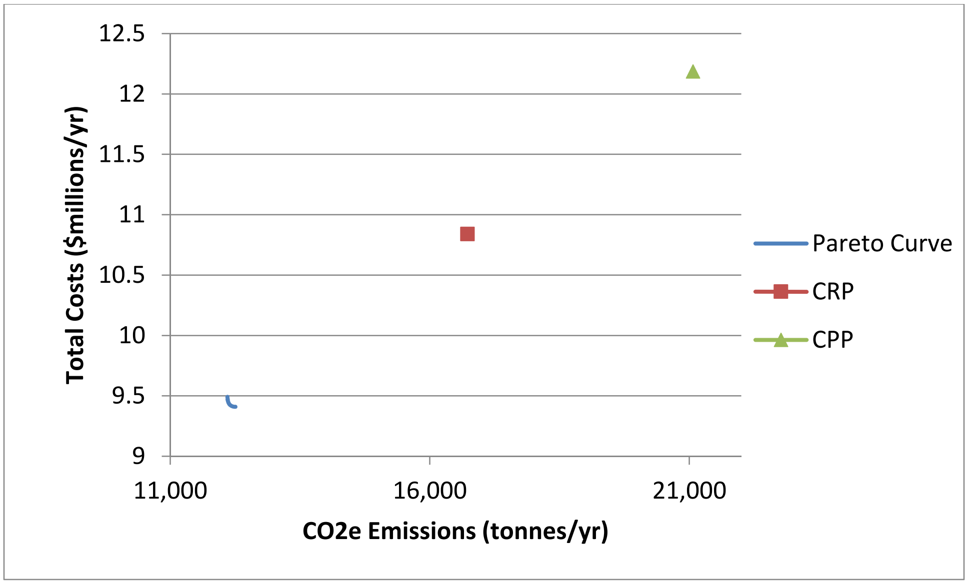

Figure 10: Results comparing the Pareto frontier to the current and past practices applied by Caltrans for Alternative Case 2 (deterioration only occurs in the right-most lane and only the lane with the highest level of deterioration is resurfaced)

3.6.2 Agency Emissions Software Change

PaLATE software was used to determine agency emissions. For sensitivity analysis, the results from the Athena Impact Estimator for Highways were examined as well (Athena 2012). Both take into account the amount of materials, hauling distances, and other factors to produce an overall emissions impact for a road project such as an overlay. Using Athena, the agency emissions were found to be 5 times higher than with PaLATE. The reason may be a wider scope for the life cycle assessment or simply different data sources associated with the various paving materials. It was found that if the agency emissions matched Athena, the overall GHG emissions per year are about 3 times higher as seen in Figure 11. An agency who wishes to apply this methodology will need to choose the software that they believe is the most accurate for their needs.

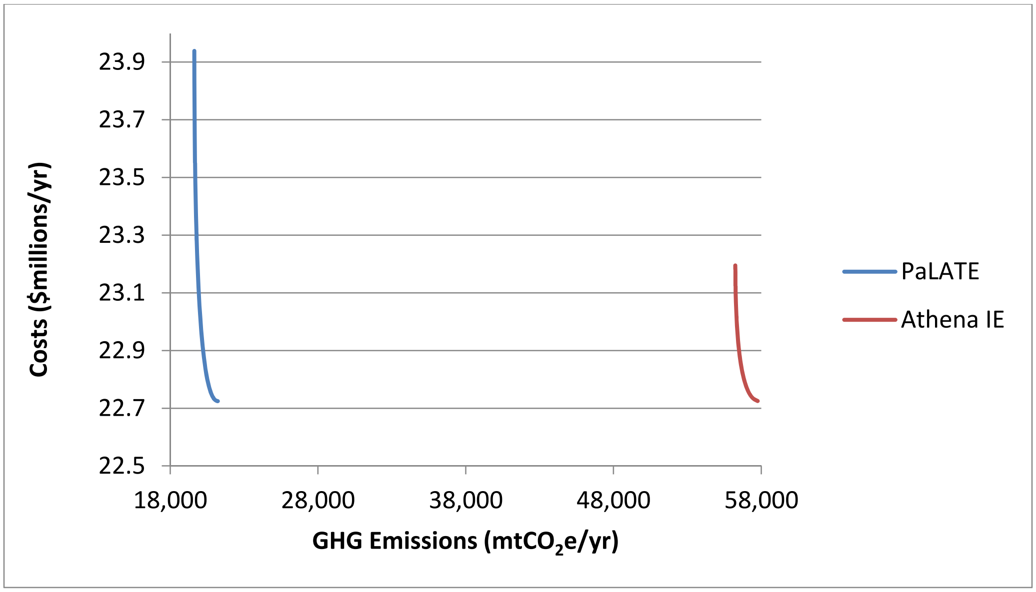

Figure 11: Alternate software for agency emissions

Chapter 4: Minimizing Total GHG Emissions Subject to an Agency Budget

4.1 Overview

The potentially optimal policies from the previous chapter assumed unlimited financial resources for the agency. This is not typically the case in practice. In this chapter, we take an alternative approach, examining the case of an agency who seeks to reduce their GHG emissions footprint where the amount of money that can be spent on rehabilitation in a given year is limited. This differs from traditional pavement management which seeks to minimize total costs subject to a budget constraint (ex. Sathaye and Madanat 2012). We show that achieving a financially sustainable and environmentally friendly pavement management system requires cooperation between legislators and transportation agencies. It is the responsibility of the agency to properly use the budget they are supplied with, but it is the responsibility of the legislation to provide the agency with sufficient funding to apply a sustainable policy. There needs to be a combined effort to ensure that tax money is allocated properly to achieve the largest reductions in GHG emissions.

The methodology used in the previous chapter should be modified to become more applicable for real-life scenarios. The previous chapter considered a single type of rehabilitation activity, but state agencies have many options at their disposal. We now show how to compare these different rehabilitation options, while still maintaining the Lagrangian dual formulation which allows for efficient solutions for large-scale networks. Using this new approach, the optimal activity and optimal timing are chosen for each road segment in the network.

4.2 Problem Formulation

Similar to chapter 3, this chapter uses a continuous time, continuous state, infinite-horizon formulation. The problem is formulated as an objective function subject to two constraints, as shown in Equations 15-17. Equation 15, the objective function, is the sum of the total yearly emissions, Q_{jk}, for all facilities j=1,…,J, choosing from potential rehabilitation actions, k=1,…,K. Q_{jk} consists of the user emissions, W_{jk}, and the agency emissions associated with applying the rehabilitation action, A_{jk}. W_{jk} is an integral from 0 to τ and A_{jk} is a function of the number of lanes of the roadway and the chosen action, k. τ_{jk} is the decision variable, and is the interval of action k for segment j. Emissions are annualized by dividing by τ. Equation 16 is the budget constraint, where M_{jk} is the cost of action k for segment j. The final constraint bounds the potential solutions between 0 and τ_{jk}^{e} (the optimal timing where total emissions are minimized). Note that τ cannot equal 0, as it would render the objective function undefined.

$$\min_{\tau_{jk}} \sum_{j=1}^{J}\{\mathrm{Q}_{jk}(\tau_{jk})\} = \sum_{j=1}^{J}[W_{jk}(\tau_{jk}) + A_{jk}(\tau_{jk})]\left(\frac{1}{\tau_{jk}}\right) \qquad \text{Eq(15)}$$

$$\text{s.t.} \quad \sum_{j=1}^{J}\left\{\mathrm{M}_{jk}(\tau_{jk})\left(\frac{1}{\tau_{jk}}\right)\right\} \leq F \qquad \text{Eq(16)}$$

$$\tau_{jk} \in (0, \tau_{jk}^{e}] \qquad \text{Eq(17)}$$

The scope of considered roughness for user emissions is shown in Figure 12. The emissions associated with roughness below the best-achievable level after rehabilitation are beyond the control of the agency. Therefore, these emissions are not included in the optimization. However, different rehabilitation actions have different respective best-achievable levels of roughness. S_1^* is the best-achievable roughness level among all the potential actions. S_k^* is the best-achievable level after action k. Reaching S_1^* is still within the agency's control, so if they choose to apply action k, the emissions associated with the difference between S_1^* and S_k^* are included.

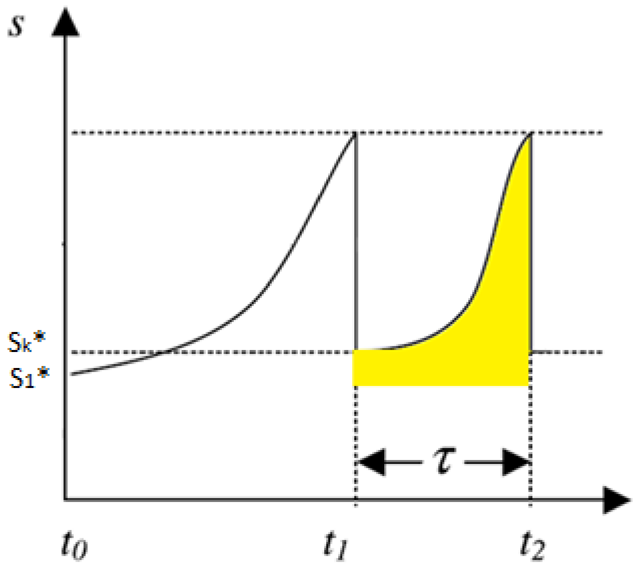

Figure 12: Scope of included user emissions

4.3 Solution Methodology

In the previous chapter, we used a similar Lagrangian duality solution methodology to that applied by Sathaye and Madanat (2012). Here we maintain a Lagrangian dual methodology, but solve it in a different manner to allow for the addition of multiple rehabilitation activities. For a given budget at optimality, all facilities in the network will have the same value of Λ, so the problem can be treated as separable. We solve for the optimal timing τ of action k on segment j, given $\Lambda = \Lambda_1$,for all actions k=1,…,K. The optimally timed action which has the lowest value of $D(\Lambda)$ is retained. The financial budget, F, is back-calculated by taking the sum of M_{jk} for all j at Λ_1.

$$D(\Lambda) = \max_{\Lambda} \left\{ \inf_{\tau_{jk}} \sum_{j=1}^{J} Q_{jk}(\tau_{jk}) + \Lambda\left[\sum_{j=1}^{J} M_{jk}(\tau_{jk}) - F\right] : \tau_{jk} \in (0, \tau_j^e] \ \forall j = 1 \dots J \right\} \quad \text{Eq(18)}$$

$$s.t. \ \ \Lambda \geq 0 \quad \text{Eq(19)}$$

4.4 Case Study

The case study is the same Californian 1,600 lane-km sample of flexible pavement segments. Data for rehabilitation actions were obtained from a study of Californian roads which gives the best-achievable condition after the activity is performed and the rate of deterioration (Tseng 2012). The rehabilitation actions considered are 5 different thicknesses of overlays (3cm, 4.5cm, 7.5cm, 10.5cm, 15cm). Although the only rehabilitation options shown for the case study are different thicknesses of resurfacing, the methodology holds for other types of activities, such as seal coating or full-depth reconstruction. As before, routine maintenance is assumed to be included in the deterioration function. User and agency emissions and costs are the same as the previous chapter.

4.5 Case Study Results

The optimization chooses the optimal action (and corresponding optimal timing for that action) for each segment at each agency budget value. The results from the case study found that the 3cm is always the optimal action for every segment at every potential budget value. The graphical results are shown in Figure 13. As the agency budget increases, total emissions decrease until the emissions-minimizing point is reached. For the case study, the emissions minimizing point was found to be $23M/yr spent on rehabilitation. An agency could choose to rehabilitate their roads even more frequently under higher budget values, but would see increases in total emissions by doing so. The slope of the curve is the amount of GHG emissions that could be saved per additional dollar spent by the agency. The results exhibit diminishing returns to scale. For example, an additional $1M/yr results in a reduction of 100,000 mtCO_2e/yr when going from $1M/yr to $2M/yr, but only reduces the total emissions by 2,500 mtCO_2e/yr when going from $10M/yr to $11M/yr. An agency is unlikely to operate near the emissions minimizing point since they will get little additional GHG emissions saved for the extra money they would spend.

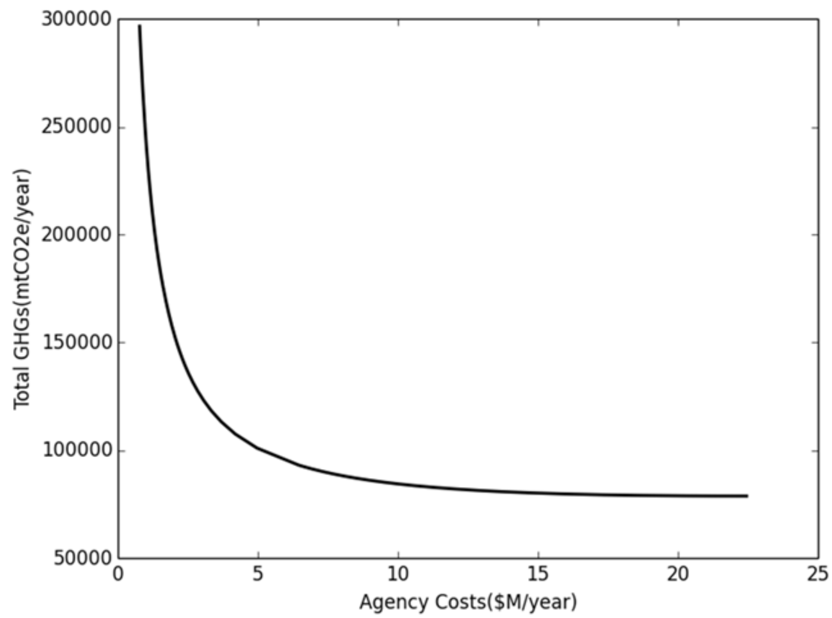

Figure 13: Case study results comparing agency budgets to total GHG emissions

The agency is responsible for optimally using the budget they are allocated, but they do not control the size of that budget. A curve, like the one shown in Figure 13, can help the agency and legislation work together to make budget decisions. Each point on the curve corresponds to a set of optimal actions and action intervals which the agency would apply under a potential budget value. This means that the entity assigning the budget is also choosing the actions that the agency will take, and the corresponding yearly GHG emissions. The graph gives the agency a way to visualize and quantify the GHG emissions under a given budget as well as determine the potential reductions if additional funds are provided. Also, this agency would now have the potential to enter a cap-and-trade system. Another agency or corporation could purchase carbon credits by supplying the agency with the funds to use for rehabilitation. As an example, if the agency currently has a budget of $5M/yr, each year they would be able to sell 8,000 mtCO_2e worth of credits for $1M since that would be the reduction from increasing their budget to $6M/yr.

4.5.1 Comparison to Alternative Investments

Another benefit is comparing investments in rehabilitation policy with other alternatives within the agency's scope. As an example, if the agency received a grant for $5M/yr that it could spend on any activity with the goal of reducing emissions, they could either invest in pavement rehabilitation or in an alternative project such as replacing conventional roadway lighting with LEDs, incentivizing switching to alternative fuels, etc. The arrows in Figure 14 are a graphical representation of an alternative project (in this case a project that would cost $5M/yr and reduce GHG emissions by 50,000 mtCO_2e/yr). If the current operating budget was $2M/yr (Arrow 1), the arrow would fall above the curve, so using the money for rehabilitation would result in greater emissions reductions. However, if the budget was $3M/yr (Arrow 2), the arrow would fall below the curve, suggesting that an alternative project would be a better investment.

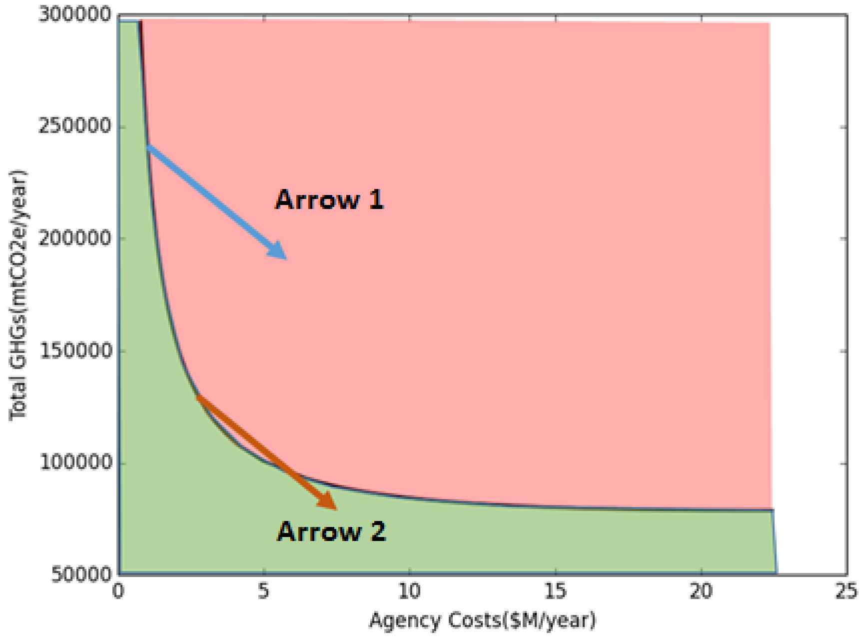

Figure 14: Comparing rehabilitation policy to alternative projects

4.5.2 Effect of Budget on Road Condition

In addition to GHG emissions, the agency would want to look at the effects of budget values on road condition. Figure 15 shows a "heat map" of the distribution of trigger roughness values for different agency budgets, where a trigger roughness is the level of roughness at which a rehabilitation action will be performed (i.e., the condition of segment j when exactly τ_{jk} years have passed). As the agency budget decreases, the trigger roughness values for the segments increase. Additionally, the range of trigger roughness value becomes wider. At the point where emissions are minimized, there is still a range of optimal trigger roughness values. This confirms the result from the previous chapter, which found that using a universal trigger roughness (i.e., applying the same trigger roughness value to every road in the network) is always sub-optimal.

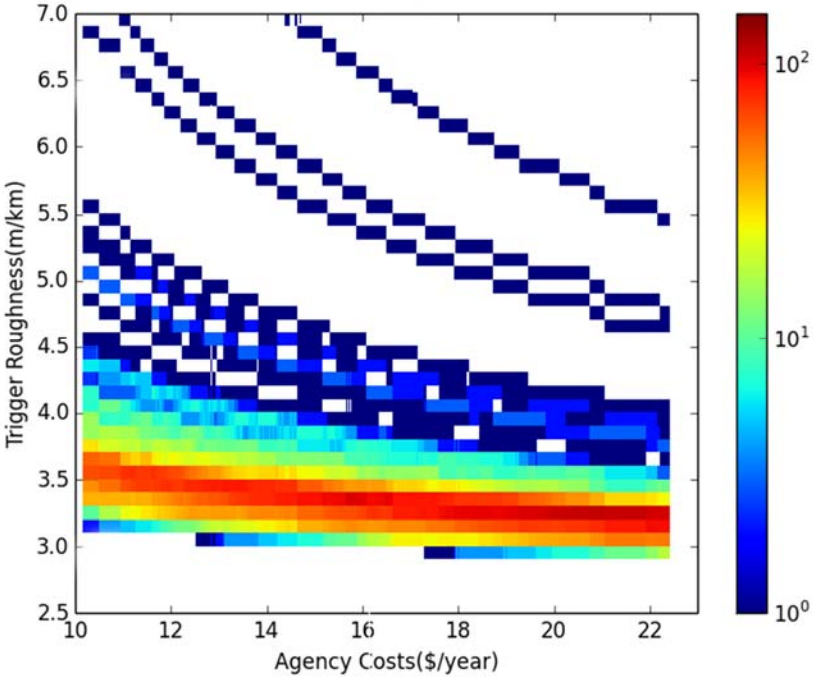

Figure 15: Heat map of the effect of agency budget on pavement condition

4.6 Uncertainty and Sensitivity Analysis

The parameters tested for sensitivity analysis were the deterioration rate, best achievable roughness level and percentage change in fuel consumption. To represent uncertainty with respect to the best achievable roughness level and deterioration rate, we assume that each is normally distributed with the mean being the value assumed in the case study and the standard deviation being 25% of the assumed value. The predetermined policy, as described in Chapter 3 is applied here as well. Figure 16 shows the results of the sensitivity analysis. The results show that the optimal policies are robust to deterioration rate and best achievable roughness level. The black line represents the predicted value of the GHG emissions, with the red lines representing the values of emissions for the simulations. The uncertainty affects the optimal policies when the budgets are high. Figure 17 shows a zoomed-in portion of Figure 16 when the agency budget is between \$15M/yr and \$23M/yr. An agency may not be guaranteed to see the reductions they expect from spending more money in this range. For example, spending an additional \$4M/yr, from \$15M/yr to \$19M/yr, would have an expected reduction of 1000 mtCO2e/yr, but the emissions from the simulations at \$19M/yr had a range of 9000 $mtCO_2e$/yr. Therefore, the increased spending may lead to no reductions (and even increases) in GHG emissions.

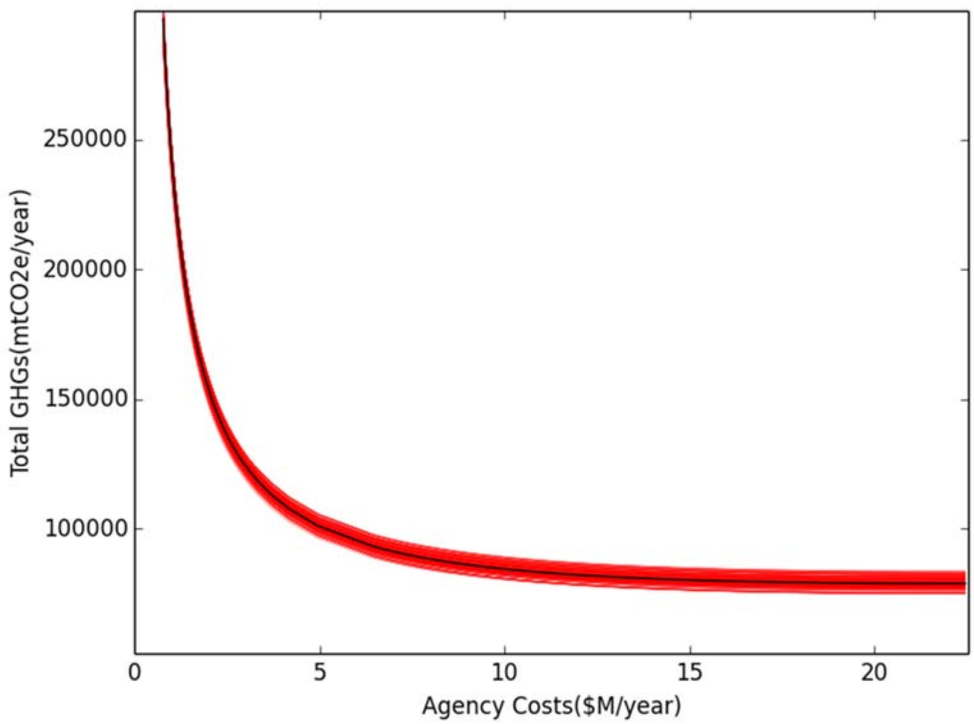

Figure 16: Sensitivity analysis for deterioration rate and best achievable roughness level

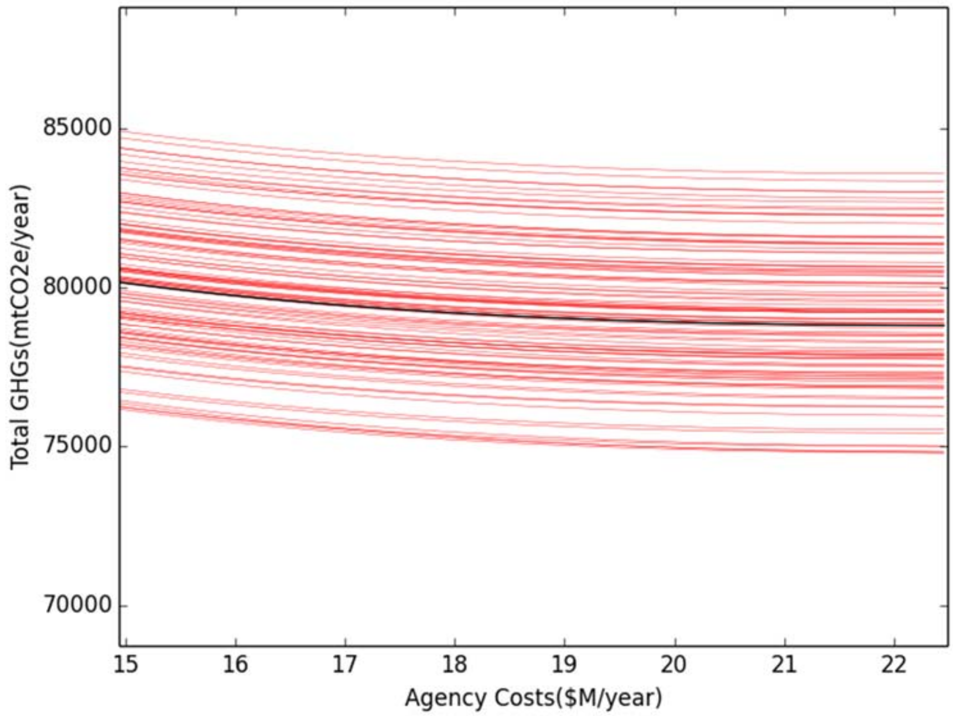

Figure 17: Zoomed-in portion of Figure 16, focusing on where budgets are near the emissions optimizing point

The Zaabar and Chatti (2014) study found that the effect of change in fuel consumption due to roughness is between 2-3% and 1-2% for light and heavy vehicles respectively, so for sensitivity analysis we assumed that the effect of roughness on fuel consumption is uniformly distributed between the values instead of using the midpoints. Again, we assumed that the agency applies the predetermined intervals chosen by the model. The model is robust to fuel consumption as 95% of the simulations resulted in GHG emissions within 500 mtCO_2e/yr of the predicted value from the optimization.

4.6.1 Sensitivity to Changes in Pavement Technology

New pavement technologies, such as warm-mix asphalt (WMA), could affect rehabilitation policy. WMA uses a lower mixing temperature than traditional hot-mix asphalt and in a best case scenario, has the potential to reduce total GHG emissions from an asphalt mix by up to 20% (Rodriguez-Alloza 2015). Figure 18 shows the effect of using WMA for rehabilitation on the case study, assuming a 20% reduction in GHG emissions from asphalt. There is almost no benefit until the agency budget is greater than $10M/yr. This is because when the budget is low, there are few rehabilitations performed each year, so the user emissions are the main contributors to the total. Near the emissions minimizing point, using WMA can result in savings of up to 3,000 mtCO_2e/yr, since there will be a sufficient number of rehabilitations performed each year. However, it is unlikely that an agency will be operating at this point on the curve. The value of carbon is the inverse of the slope of the curve. Beyond an agency budget of $10M/yr, the cost of saving an additional metric ton of carbon is upwards of \$700/mtCO_2e which is higher than carbon has ever been valued on the market. There may be other benefits to WMA, such as improved workability and safety, but with respect to GHG reductions in pavement rehabilitation policies, it shows little benefit.

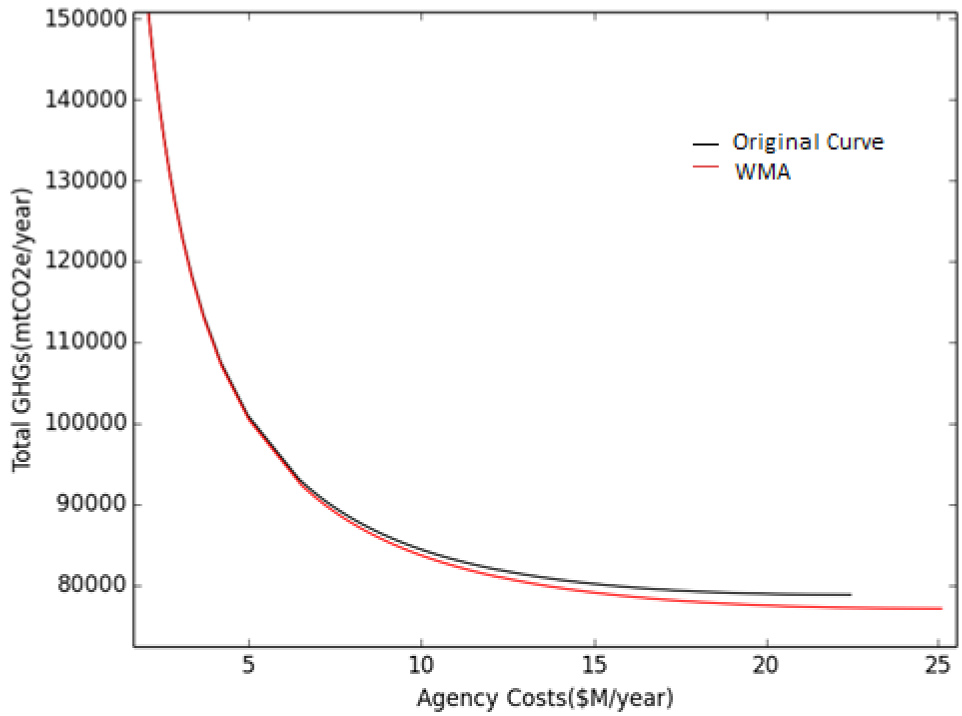

Figure 18: Potential effect of warm-mix asphalt technology on rehabilitation policy

The cost of asphalt may change with the recent drop in oil prices. Bitumen is a product of petroleum refining and is also the most expensive part of the asphalt mix. Figure 19 shows the results assuming a 20% reduction in rehabilitation costs. The effect is significant for low budget values, but is less noticeable as the agency budget increases. At a budget of \$1M/yr, the 20% reduction in costs would reduce the GHG emissions by 50,000 mtCO_2e/yr. When the budget is \$15M/yr or higher, the effect is negligible. This occurs because a reduction in costs stretches the budget farther, allowing more roads to receive rehabilitation and reducing GHG emissions. It is effectively giving the agency more money to spend.

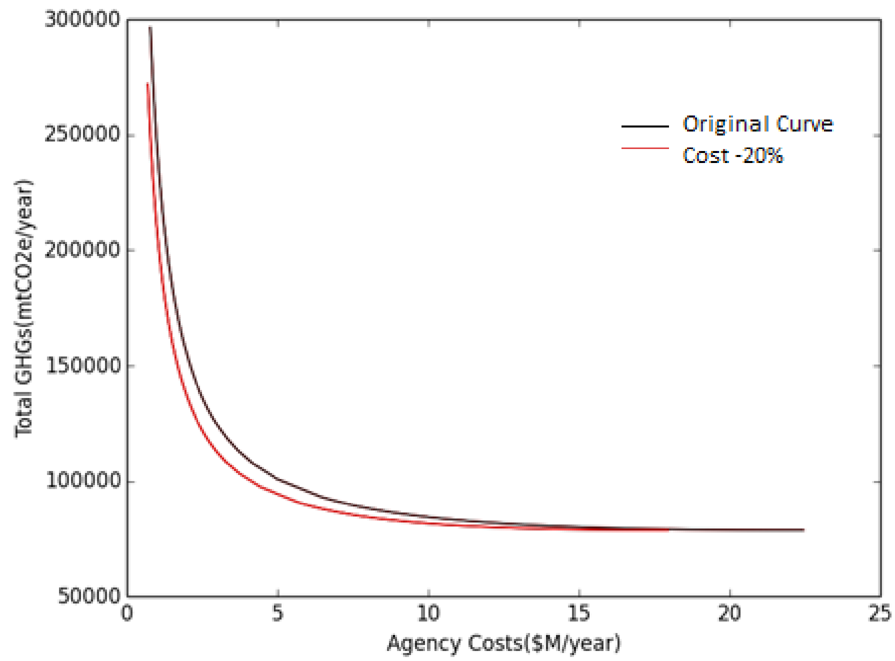

Figure 19: Effect of reducing rehabilitation costs by 20%

Chapter 5: Discussion

5.1 Contributions of Dissertation

Two feasible approaches that an agency could take to incorporate GHG emissions into their pavement management systems are presented here. States use pavement management systems to decide when to rehabilitate their roads. The first looks at minimizing total costs subject to a total emissions constraint. Traditional pavement management systems seek to minimize total costs, but many agencies are starting to consider ways to reduce GHG emission impacts. The results of the optimization create a Pareto frontier where there are a range of potentially optimal solutions that an agency can choose. Along this Pareto frontier, the agency cannot reduce total costs without increasing emissions or reduce total emissions without increasing costs.

The second approach looks at an agency which wants to reduce its GHG emissions impacts but is constrained by a rehabilitation budget. This approach may be more realistic as there are very few agencies which will have unlimited financial resources. An agency can use the results from this type of analysis to quantify the budget needed to hit its GHG emissions target.

5.1.1 Trigger Roughness Implications

The most common policy used in practice, the universal trigger roughness policy, was shown to be sub optimal. First, for a given segment, the optimal trigger roughness for minimizing total societal costs is not the same as the optimal trigger roughness for minimizing total societal emissions. Furthermore, both the optimal trigger roughness values for minimizing societal costs and emissions vary by segment. An additional unit of IRI results in much larger increases in user costs and emissions for a high traffic road than for a low traffic road. When trying to fit one strategy to all segments, some segments will be rehabilitated too infrequently, while others will not be rehabilitated frequently enough. This was demonstrated by comparing the current and former Caltrans trigger roughness policy to the Pareto curve created by optimization in this research.

When constrained by an agency budget, this becomes an issue of proper resource allocation. Lower budget values force the agency to perform less rehabilitation actions each year, therefore, rehabilitating the segments where the reductions in GHG emissions will be the most significant is crucial. The range of trigger roughness values also widens as the budget is reduced. At every possible budget value there is still a range of trigger roughness values, which confirms that a universal trigger roughness policy is sub optimal. The issue of condition may become a factor for a small number of segments where the trigger roughness surpasses what is typically seen on paved roads in developed countries. In this case, the agency may have to allocate some of the budget to these roads sub optimally, but since only 2% of the case study roads fall into this category, it would not greatly affect the yearly emissions.

5.1.2 Intensity of Resurfacing

The literature that focused on minimizing total costs found that it is always optimal to resurface to the best achievable roughness level (Li and Madanat 2002, Ouyang and Madanat 2006, Gu 2012). The model from Chapter 3, which aimed to minimize total costs subject to an emissions constraint, came to the same conclusion. However, in Chapter 4, when focusing on minimizing total emissions subject to a budget constraint, the results showed that it was always optimal to apply the thinnest resurfacing (3 cm), even though the 15 cm resurfacing is the action that would result in the best achievable roughness level. To understand why this is the case, we can look at the cost of and emissions from each type of overlay.

In the roughness progression model used in Chapter 4, the 15 cm overlay will deteriorate 22% slower and have a 0.1 m/km better condition after resurfacing, but will cost about twice more and have 5 times the amount of GHG emissions as the 3 cm overlay. In this case, an agency can perform a 3 cm resurfacing on two segments for the same cost as a 15 cm resurfacing on one segment. This is important when the budget is low because keeping more roads in good condition reduces user emissions. When the budget is not binding, the 3 cm overlay remains optimal because now actions are being performed very frequently, and the agency emissions from overlays are the controlling factor. Even going from a 3 cm overlay to a 4.5 cm overlay, costs per resurfacing increase by 14% and emissions increase by 50%. The benefit from slower deterioration does not offset these additional costs and emissions. These results match what is sometimes seen in practice by the WSDOT which applies early, thin overlays to their pavements.

5.1.3 Using Carbon Price

There are two possible definitions for carbon price, the societal carbon price and the agency carbon price. The societal carbon price is the carbon price found by taking the slope of the Pareto curve in Chapter 3, and includes both user and agency costs combined. This carbon price is useful if the agency is not constrained by budget and is trying to decide which potentially optimal policy to use. The agency can then pick a price of carbon from a study or an auction and choose to operate at the point on the curve corresponding to that slope. An agency can also look at the price of carbon that corresponds to a given emissions target to determine if the target is practical. If the price of carbon at a given emissions target is higher than carbon has ever been valued on the market, the target can be deemed too ambitious.

If the agency has limited financial resources, the agency carbon price (price of carbon excluding user costs) resulting from taking the inverse of the slope of the curve in Chapter 4 is appropriate. The agency carbon price can help the agency make a case for a higher budget if they can show that the price of carbon is very low at their current operating point. Furthermore, the agency can use the curve to evaluate other potential investments to reduce GHG emissions within their scope to decide if the money should be spent on rehabilitation policy. If it is unable to receive a higher budget from the legislation, the formulation would allow it to sell carbon credits and use that money for rehabilitation policy. The agency can do so by quantifying the reduction in GHG emissions from spending the additional money that it receives from the sale.

5.1.4 Policy Implications

Reducing VKT is a policy which results in significant reductions in both costs and emissions. Less vehicles traveling on the road not only means less emissions from the tailpipes, but also less of a need for the agency to resurface as frequently. Therefore, total user costs and total agency costs are lowered. While total user costs decrease, the individual cost per user will increase from the longer resurfacing intervals. However, since the changes in fuel economy are so gradual (1-3% per unit of IRI) it is unlikely that the users will notice. Another policy would be to promote better fuel efficiency for vehicles. Improvements in fuel economy are effectively equivalent to reducing VKT. For example, a 10% improvement in fuel economy results in the exact same user emissions as a 10% decrease in VKT.

Improved construction standards also result in significant reductions in both costs and emissions. The benefits are twofold. Pavements in better condition have lower user costs and they also deteriorate at a slower rate. Since the pavement will deteriorate slower, the agency will not have to resurface as frequently. The agency would benefit from incentivizing better levels of roughness after resurfacing. They could do so by offering, as a bonus, part of the money that they will save from resurfacing less frequently.

5.2 Uncertainty

The parameters tested for uncertainty in the first part of the dissertation were the deterioration rate, the best achievable roughness level, and traffic volumes. The solutions were found to be robust with respect to all three parameters, however, uncertainty in the deterioration rate can lead to higher emissions than those predicted by the model. For sensitivity analyses in the second part of the dissertation, the deterioration rate, the best achievable roughness level, and the effect of roughness on fuel consumption were considered. The solutions were robust with respect to these parameters, with deterioration and best achievable roughness level having much smaller effects here than for Chapter 3. This means that the equations from Tseng (2012) are less sensitive to uncertainty in the parameters than the equations from Paterson (1987).

The effects of changes in pavement technology are dependent on the budget. WMA, which has relatively lower emissions than hot-mix asphalt, only results in significant changes in emissions when agency budgets are high. This is because when budgets are low, there are very few rehabilitation actions being performed. Infrequent rehabilitation actions lead to poor road conditions and high user emissions. Changes to cost of asphalt are significant only when agency budgets are low. Lowering the cost of rehabilitation has a similar effect to increasing budget since the agency will now be able to perform more actions in a given year.

5.3 Application

For both approaches, the case studies had road segments which should be rehabilitated with very little frequency (e.g., $\tau \approx 50$ years). However, the data collected to determine the rate of deterioration did not have a segment which was allowed to deteriorate for 50 years with no intervention. Weathering may prevent these long rehabilitation intervals from being feasible. More data are needed determine how pavements would deteriorate if left without rehabilitation for long time periods and if there were minor treatments which could work as placeholders until it is time for a rehabilitation activity.

If an agency wanted to apply one of the approaches presented in this dissertation, it would need to first collect data on roughness progression and improvement. Sensitivity analysis showed that for a given roughness progression or improvement model, the results are robust, but two different models with two different mathematical structures will produce significantly different results. The progression model from the Paterson (1987) equation was very different from the model from the Tseng (2012) study. An agency needs to choose the equation that most closely fits its roads, or collect enough data to create its own models of roughness progression and improvement.

The agency will also need to decide which LCA software it thinks is the most accurate. In this case it would be logical for to perform a full LCA on a rehabilitation activity and see if it matches one of the software packages on the market. Results showed that different software results in different values of GHG emissions from resurfacing. Athena IE produced results that found resurfacing GHG emissions to be 5 times that of PaLATE. This lead to a difference of about 3 times more emissions when running the optimization.

After deciding which models to use and where to get the values for agency emissions, the agency will need to decide which of the cases will occur on its roads. If their roads are very sturdy and the roughness only progresses due to environmental factors, it should use AC1. If the agency is trying to save money and thinks that it can trust the contractors to perfectly line up elevations when only resurfacing a single lane, it should use AC2. Most likely, it will use the base case which assumes that the majority of deterioration occurs in the truck lane and the entire roadway section will be rehabilitated once the truck lane reaches an unacceptable level of condition.

Chapter 6: Concluding Remarks

The first part of the dissertation presented a framework for including GHG emissions minimization in pavement resurfacing policy. The Lagrangian dual solution methodology is used which allows for efficient solutions to large-scale problems. A realistic deterioration model is used and a case study is performed on a subset of California highways. The recent resurfacing policy change in California (going from a trigger roughness of 3.5 m/km to 2.7 m/km) was shown to be beneficial for reducing both total costs and total emissions. Although an improvement over the past policy was shown, the recently adopted policy was still found to be sub optimal. Further reductions in total costs and total emissions can be achieved by switching to a policy that is located on the Pareto frontier. This switch would keep the same threshold-based decision making process, but specify a different optimal trigger roughness value for each segment.

It was shown how the societal value of carbon can be used to decide which resurfacing policy to use. The link between an agency being given an emissions budget and how that budget implicitly decides the societal value of carbon was also discussed. How agencies can use this optimization method to evaluate their budget needs in order to operate optimally was also shown. For agencies which already use a cost-optimizing pavement management system, this section shows how they can incorporate GHG emissions into their accounting. Sensitivity analyses determined that the solutions are robust with respect to best achievable roughness level and traffic changes. The solutions are also robust with respect to uncertainty in the deterioration rate, but for that case, most of the simulated scenarios resulted in slightly higher emissions than the model predicted.

The second part of this dissertation presented an approach that can be taken by an agency whose goal is minimize their total GHG emissions from rehabilitation while operating under a financial budget. The results provide the optimal timing along with the optimal actions to take for every road segment in the network. The inclusion of multiple types of activities makes the methodology more applicable for real-world scenarios while still retaining the Lagrangian dual formulation for efficient solutions. An agency can use these results to make the case for a higher rehabilitation budget to achieve their emissions reduction target. It is also possible to implement a system where the agency could sell carbon credits, by quantifying the emissions reductions from increasing its operating budget and price accordingly. This methodology also allows it to compare spending money on rehabilitation or another project within their scope to determine which investment will result in greater emissions reductions.

A case study, using the same set of California roads as from the first part, was examined. It was found that it is optimal to apply frequent, thin resurfacings. This is contrary to the literature for minimizing costs, which found that it is always optimal to rehabilitate to the best achievable roughness level, but matches what is done in practice by the WSDOT. Sensitivity analyses showed that the solutions are robust with respect to deterioration rate, best achievable roughness level, and effect of roughness on fuel consumption. The effect of using WMA was determined to only be significant when agency budgets are high, since at low budget values rehabilitation is infrequent. However, if asphalt prices fall or the agency finds a way to reduce costs, the potential savings in GHG emissions are significant when the budget is low.

Even though the analyzed cases focused on California, the optimization models are applicable to other locations. It was shown that a universal trigger roughness is not optimal, which is a policy used by many countries. Furthermore, the framework allows for the inclusion of additional policies, such as reduced VKT. It was determined that lowering the total VKT, improving construction standards, and improving vehicle fuel economy will always result in improvements for total costs and emissions for both the users and the agency. These policy changes can help the agency reach lower levels of GHG emissions than the emissions minimizing point on the curve.

6.1 Future Work

Economies of scale (EOS) are not currently accounted for, but could prove to be significant in the case of a binding agency budget. If an agency can resurface more than one segment at a time, it can reduce the fixed costs, allowing more segments to be resurfaced for less money. EOS are a function of work production. Since many agencies, including Caltrans, typically perform rehabilitation overnight, it will be important to see how many lane-km they are capable of paving in the overnight timeframe. Factors that affect work production include distance from the equipment depot to the construction site, distance from the asphalt plant to the site, the type of rehabilitation and how thick the new layer will be, width of the roadway, and weather.

Another assumption of this work is that pavements are perpetual. This implies that the road is designed sufficiently strong such that the damage is mainly contained within the surface layer and does not permeate to the underlying layers such as the base and sub-base. While this may be the case in developed countries, it is unlikely to occur in developing countries where resources are scarce. If the pavement is not sufficiently strong, when a resurfacing is performed, the pavement's condition will improve but underlying damage will still remain. Therefore, the level of roughness after resurfacing gets worse and the rate of deterioration becomes faster. The pavement is only brought back to new condition when a full-depth reconstruction is performed. A steady-state methodology can still be used, but now the steady state begins and ends with reconstruction instead of resurfacing. In between two reconstruction activities, the agency will perform a number of resurfacings which need to be optimized.

Another extension of this work would be to include other environmental factors such as particulate matter (PM). For PM, it will be necessary to consider where to source materials from as well as the population within a given distance from a road. It may be optimal to use an asphalt plant that is located farther from the construction site, provided that it has a surrounding neighborhood which will be less affected by the PM. This is contrary to current policies, which typically choose the closest or cheapest option. The optimization should find that it is important to keep certain roads in good condition if they are near highly populated areas to reduce the PM impacts since PM is most dangerous when there is exposure over an extended period of time. Standard non-linear programming such as Lagrangian duality will no longer be sufficient since there will be a 3rd criterion as well as spatial and temporal effects. A more rigorous solution methodology, such as the genetic algorithm, will need to be applied.

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Appendix A: Single-facility Case

To demonstrate the differences in total costs and GHG emissions between roads under different conditions, 8 different 1km long pavement segments were examined as shown in Table A-1. These encompass the main types of roads seen in California. Agency costs for resurfacing were found to be lower by Hand et al. (1999) for rural roads, but emissions remain the same. Rural roads see fewer motorists, so they should have lower user costs and emissions as well. A section is classified as rural if the surrounding area has a population center with less than 5000 people or a density below 1000 people per square mile. Different numbers of lanes are also examined, as the agency costs and emissions vary depending upon the physical characteristics of the segment. Rural 4 and 5 lane sections are not included as there is typically insufficient traffic in rural areas to warrant a high number of lanes. Even 3-lane rural roads are unlikely to exist; out of the 300 segments from District 4 that were considered, none fell near a town with a population density under 1000 people/mi^2. Route 221, near the junction with Route 121 in Napa, was the closest to a rural road from the data given, with a population density of approximately 4,000 people/mi^2 and the lowest AADT of the 3-lane segments considered (U.S. Census Bureau 2013). Allowing for the possibility that a 3-lane rural road may exist somewhere in California, this segment was treated as rural for comparative purposes amongst single facilities.

Table A-1: Sections Included in Analysis for Single Facilities

# of Lanes 1-Direction	Urban/Rural	Route	Location	County	AADT	AADTT
1	Rural	1	Jct. Rte. 116 East	Sonoma	2650	154
1	Urban	12	Jct. Rte. 80	Solano	31500	2268
2	Rural	101	Jct. Rte. 128 West	Sonoma	14000	1586
2	Urban	980	Jct. Rte. 880	Alameda	75000	5273
3	Rural	221	Jct. Rte. 121	Napa	32500	1641
3	Urban	680	Jct. Rte. 580	Alameda	165000	12540
4	Urban	80	Near Appian Way Exit	Contra Costa	190000	8303
5	Urban	80	Jct. Rte. 13	Alameda	264000	12698

Figures A-1 through A-8 show the Pareto frontiers for each segment and compare them with the Caltrans recent policy and Caltrans past policy. It can be seen that the total costs and emissions for the rural segments were about half of their urban counterparts for a given number of lanes.

The three rural segments were found to cost roughly the same amount per lane-km per year, but urban segments were found to vary.

It can be seen that for the rural locations, they usually fall close to the Pareto frontier, and in some cases lie on the Pareto frontier. CPP is on the Pareto frontier in Figure A-1 and the CRP is on the Pareto frontier for Figure A-3. The results show that the 2 DOT policies perform considerably worse for urban segments than for the segments. The urban segments' results show that CPP is operating at much higher total costs than would be optimal, as much as $1 million per year higher in the case of the 5-lane urban road (Figure A-8). The CRP policy, while also high on costs, performs most poorly with respect to emissions. It can be seen in the case of Figure A-6 that the emissions are nearly double that of any point on the Pareto curve amounting to over 250 mt CO_2e per year more than the nearest point on the curve. To gain some insight about why the CRP and CPP policies more closely fit rural roads, the optimal bounds for τ are examined.

Using the 3-lane cases as an example, the upper and lower bounds for τ were found to be 15 and 21 years respectively for Rte. 221 in Napa County 7 and 11 years for Rte. 680 in Alameda County. To reach the trigger roughness for CRP, the amount of time between resurfacings is approximately 22 years for these segments, and to reach the trigger roughness for CPP would take 26 years. The CRP and CPP policies are closer for rural segments because these sections have larger τ values due to fewer motorists. For the highly trafficked urban sections, the values for τ are considerably smaller since user costs and emissions increase quickly with higher levels of roughness.

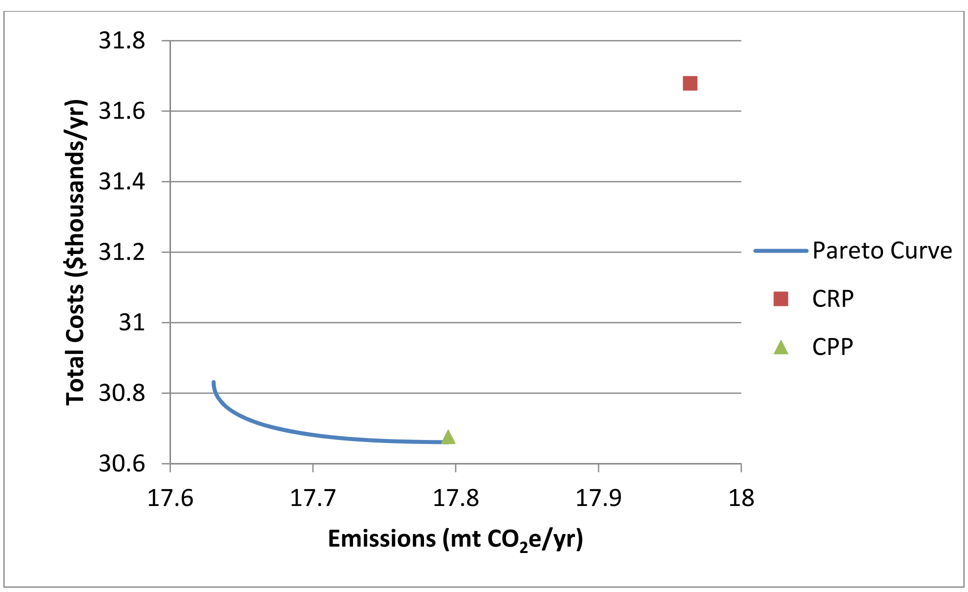

Figure A-1: Pareto Frontier as compared to CRP and CPP policies for a 1-Lane Rural Rd: Rte. 1 Sonoma County

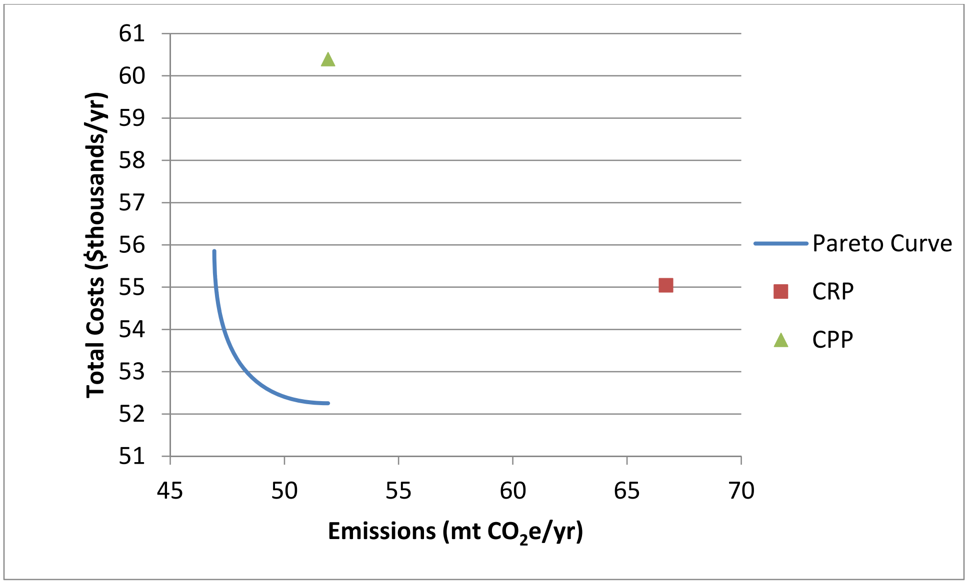

Figure A-2: Pareto Frontier as compared to CRP and CPP policies for a 1-Lane Urban Rd: Rte. 12 Solano County

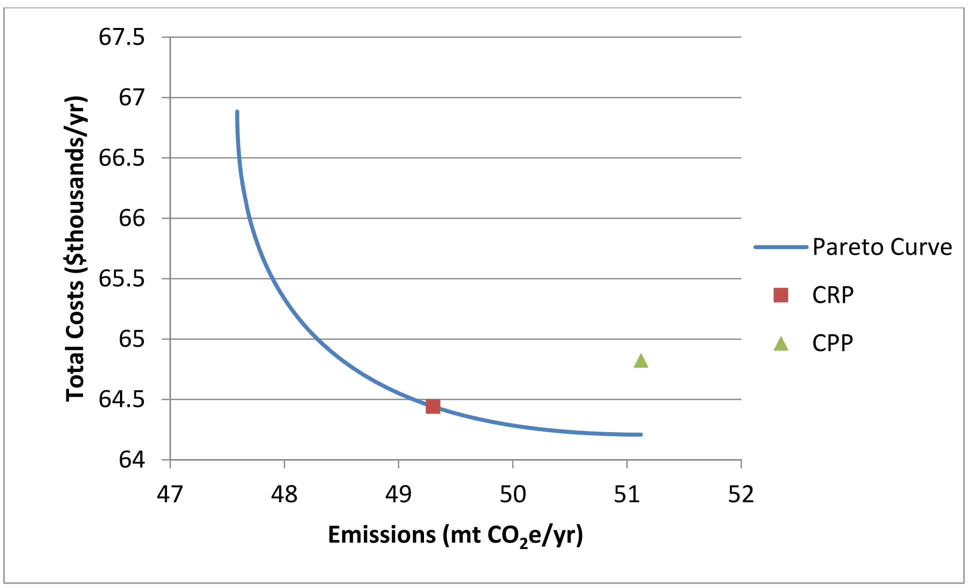

Figure A-3: Pareto Frontier as compared to CRP and CPP policies for a 2-Lane Rural Rd: Rte. 101 Sonoma County

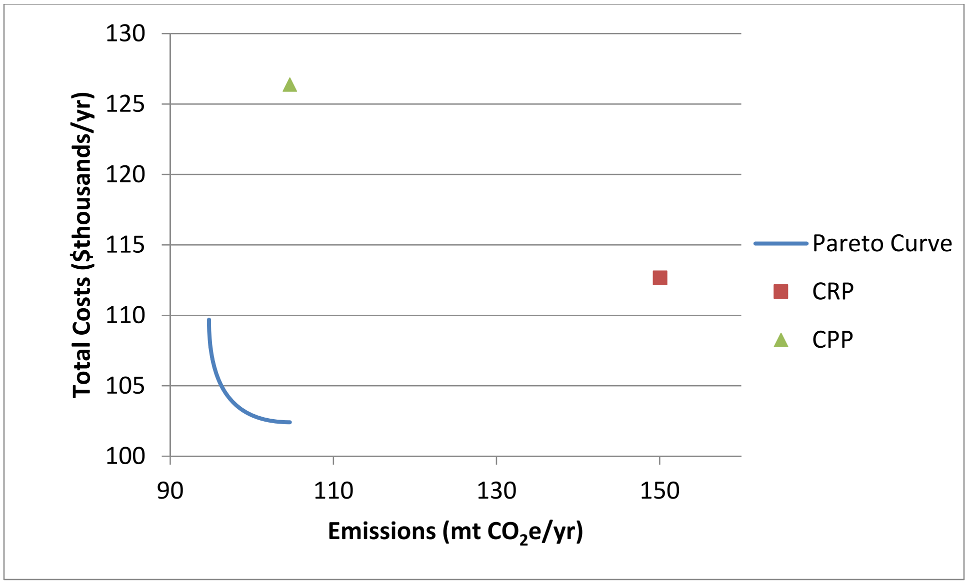

Figure A-4: Pareto Frontier as compared to CRP and CPP policies for a 2-Lane Urban Rd: Rte. 980 Alameda County

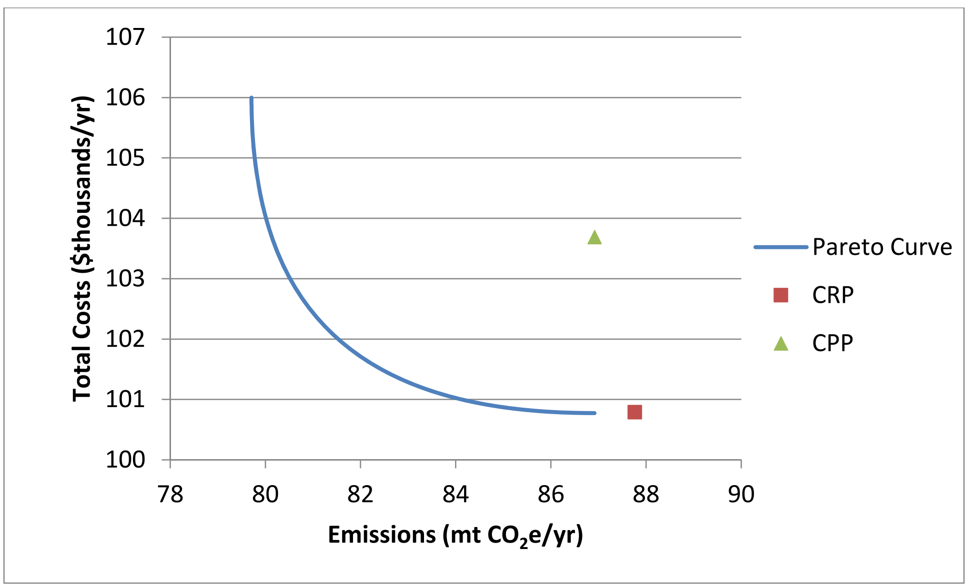

Figure A-5: Pareto Frontier as compared to CRP and CPP policies for a 3-Lane Rural Rd: Rte. 221 Napa County

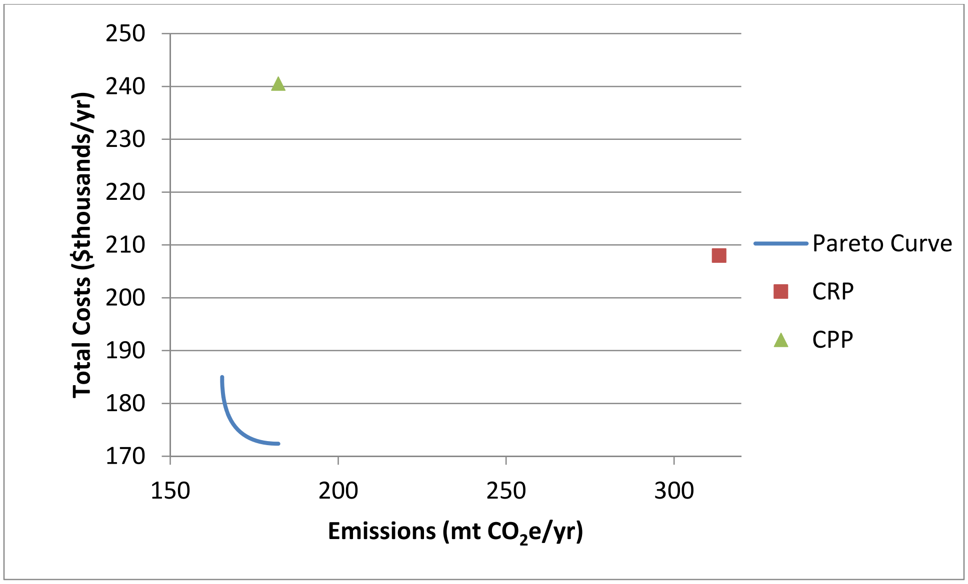

Figure A-6: Pareto Frontier as compared to CRP and CPP policies for a 3-Lane Urban Rd: Rte. 680 Alameda County

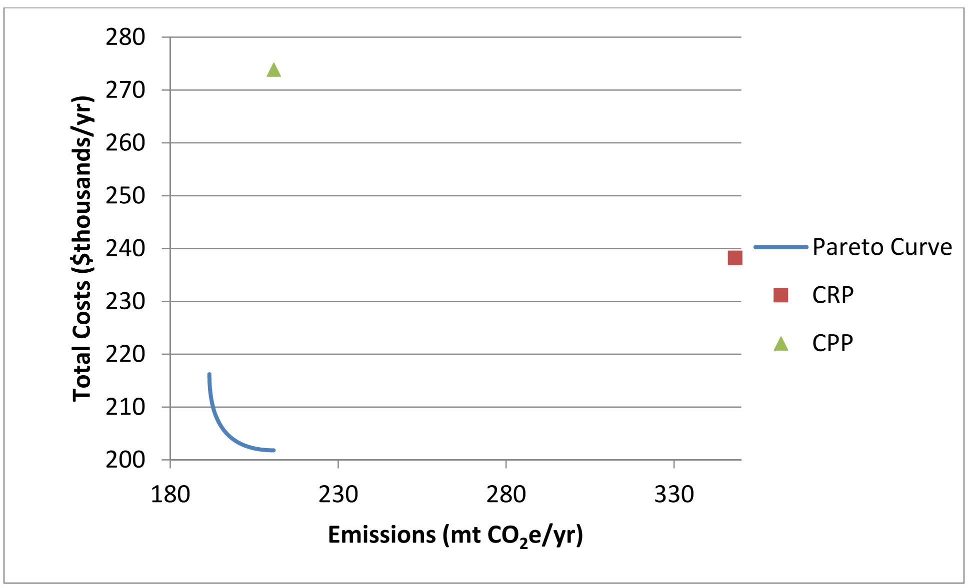

Figure A-7: Pareto Frontier as compared to CRP and CPP policies for a 4-Lane Urban Rd: Rte. 80 Contra Costa County

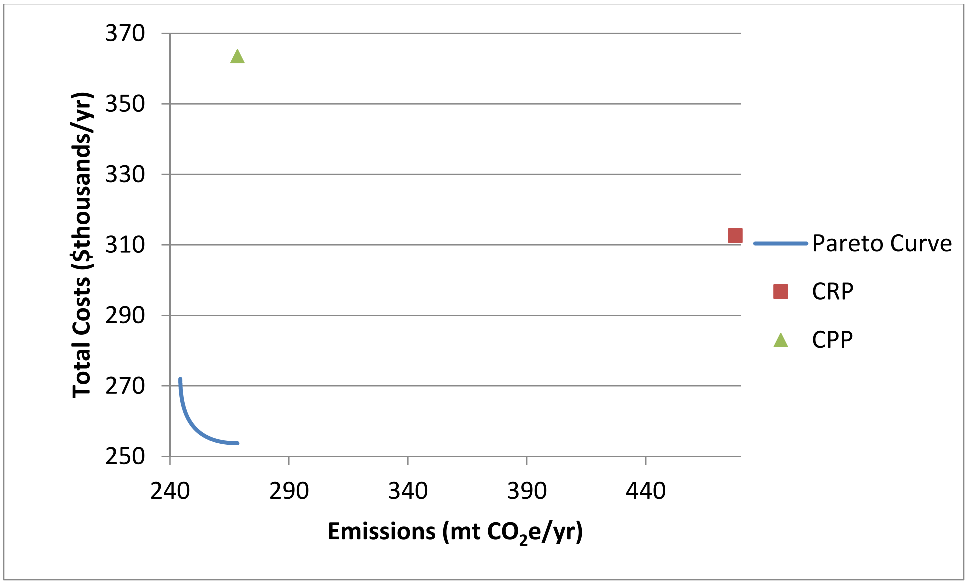

Figure A-8: Pareto Frontier as compared to CRP and CPP policies for a 5-Lane Urban Rd: Rte. 80 Alameda County