

# UC Berkeley

## UC Berkeley Electronic Theses and Dissertations

### Title

A Methodology for a Pavement Resurfacing Strategy to Minimize Life-cycle Costs and Greenhouse Gas Emissions

### Permalink

<https://escholarship.org/uc/item/73j2b9nn>

### Author

Lidicker, Jeffrey Roger

### Publication Date

2012

Peer reviewed|Thesis/dissertation

A Methodology for a Pavement Resurfacing Strategy  
to Minimize Life-cycle Costs  
and Greenhouse Gas Emissions

By  
Jeffrey Roger Lidicker

A dissertation submitted in partial satisfaction of the  
requirements for the degree of  
Doctor of Philosophy  
in  
Engineering - Civil and Environmental Engineering

in the  
Graduate Division  
of the  
University of California, Berkeley

Committee in charge:

Professor Samer Madanat, Co-Chair

Professor Arpad Horvath, Co-Chair

Professor David Dowall

Professor Adib Kanafani

Spring 2012

---

# A Methodology for a Pavement Resurfacing Strategy to Minimize Life-cycle Costs and Greenhouse Gas Emissions

---

© Copyright 2012

by Jeffrey Roger Lidicker

All Rights Reserved

## Abstract

### A Methodology for a Pavement Resurfacing Strategy to Minimize Life-cycle Costs and Greenhouse Gas Emissions

---

by

Jeffrey Roger Lidicker

Doctor of Philosophy in Engineering – Civil and Environmental Engineering

University of California, Berkeley

Professor Samer Madanat, Co-Chair

Professor Arpad Horvath, Co-Chair

---

In recent decades pavement management optimization has been designed with the objective of minimizing user and agency life-cycle costs. However, pavement management decisions also have significant impacts on life-cycle energy use and environmental emissions from pavement management activity and user vehicles. This study expands beyond optimizing pavement rehabilitation strategy for minimization of life-cycle costs to also include greenhouse gas (GHG) emissions. We extend previous work on the single-facility, continuous-state, continuous-time optimal pavement resurfacing problem to solve the multi-criteria optimization problem with the two objectives of minimizing costs and GHG emissions.

The balance between the potentially two different optimal rehabilitation policies is found through the use of a Pareto frontier, which exists in the span between the cost- and emission-optimal strategies. The Pareto frontier provides decision makers with the dollars per tonne of GHG emissions saved due to a change in rehabilitation strategy. Results using California data indicate that there is a tradeoff between costs and emissions when developing a pavement resurfacing strategy, providing a range of GHG emissions reduction cost-effectiveness options.

Case studies for a two-lane arterial and a ten-lane major highway in California are presented, where traditional hot-mix asphalt overlays are applied. The 2011 case studies are particular to California by traffic loadings and pavement durability. However, the user and agency emission and cost estimations are based on national data. Thus, generalizing the case study results should be subject to these caveats. An ordinary medium-volume metropolitan state-designed road and an extremely heavily traveled highway bearing commuters into and from San Francisco are optimized as representative situations.

Results for a one-kilometer segment of Interstate 80, in Berkeley California, with ten lanes and 273,000 light-duty vehicles and 13,100 heavy-duty vehicles per day, indicate that the life-cycle cost minimum occurs when asphalt overlays are applied every 15 years or equivalently when the pavement roughness reaches an international roughness index (IRI) of 2.7 m/km. Coincidentally, this is the same roughness Caltrans uses to decide when to apply an overlay for the state's roads. However, where any of the conditions or characteristics for any pavement

segments are different, the coincidence may cease to exist. The minimum life-cycle cost at this optimal pavement rehabilitation strategy is approximately \$490,000 per kilometer per year, at which point resurfacing activity and user vehicles would emit approximately 220 tonnes of CO<sub>2</sub> equivalents per kilometer per year. The GHG emissions minimum corresponds to an overlay interval of 22 years or the equivalent threshold roughness IRI of 3.4 m/km. The minimum GHG emissions (user emissions plus agency emissions) are approximately 200 tonnes of CO<sub>2</sub> equivalents per kilometer per year, with life-cycle costs (user costs plus agency costs) at approximately \$520,000 per kilometer per year. Agency and user emission (and cost) estimates each change in opposing directions when overlay intervals change. Thus, when each of the like agency and user attributes are added together, a minimum is guaranteed to exist.

Any pavement rehabilitation strategy that makes use of overlay intervals outside of this sub-interval defined by the life-cycle cost and GHG emissions optima are trivial in that any strategy change designed to reduce costs also reduces emissions. However, inside this special sub-interval, any change in strategy that reduces costs will increase emissions and vice versa. Thus, this special sub-interval constitutes a Pareto frontier of optimal solutions where tradeoffs are associated with each change. For example, if Caltrans is currently operating at the life-cycle cost minimum by applying an overlay interval every 15 years but decides to reduce emissions by changing the interval to every 18 years, there will be a reduction in emissions. However, it will come at a total life-cycle cost of approximately \$500 per tonne of CO<sub>2</sub> equivalents. Of course different pavement rehabilitation strategy changes will present different cost-effectiveness ratios. If the change spans points outside the Pareto frontier, the costs may be minimal or even negative. However, within the Pareto frontier, attempts to save even more emissions will increase costs per unit of CO<sub>2</sub> equivalents saved.

If a market value for CO<sub>2</sub> exists, then a unique optimal pavement rehabilitation strategy is defined. On the Pareto frontier is every possible market value as the negative of the slope of the tangent line to each point on the curve represents a market value starting with zero dollars per tonne of emissions (cost minimum) to infinite dollars per tonne of emissions (emissions minimum).

Results for a two-lane arterial road segment, also in Berkeley, which has only 25,000 light-duty vehicles and 480 heavy-duty vehicles per day, indicate that similar pavement rehabilitation strategy overlay intervals are optimal. For the life-cycle cost minimum, a 16-year overlay interval is optimal, which corresponds to a threshold roughness IRI of 2.1 m/km. For the GHG emissions minimum, an overlay interval of 25 years and its associated threshold roughness IRI of 2.5 m/km are optimal. Although the overlay intervals are not that different from the larger ten-lane interstate highway case, the threshold roughness values are more favorable in the two-lane case. The life-cycle cost minimum occurs at approximately \$80,000 per kilometer per year and is associated with approximately 51 tonnes of CO<sub>2</sub> equivalents per kilometer per year. The GHG emissions minimum occurs at approximately 47 tonnes of CO<sub>2</sub> equivalents per kilometer per year and is associated with approximately \$86,000 per kilometer per year.

A sensitivity analysis on model input parameters revealed which parameters required the best accuracy and shed light on policy decisions. Pavement deterioration rate, within a 20% variation, had a relatively little effect on outcomes. This indicates that uncertainty around the pavement deterioration rate is not very important. However, a small change in vehicle miles traveled had a large effect on outcomes. Other results highlighted the contrast between strategy decisions for various pavement and vehicle technologies. For example, it is found that, in both

case studies, improving vehicle fleet fuel economy will save total (tailpipe plus pavement) emissions. The two-lane case showed a larger percentage of relative reduction in emissions but the ten-lane case was found to have a larger total reduction in emissions. However, an improved fuel economy for the vehicle fleets means that the effect of roughness on fuel consumption is less. Thus, the GHG emissions associated with pavement management become a larger share of the total emissions. This means that at the emissions optimal, the pavements are allowed to become rougher before being rehabilitated again. Thus, to counteract the expected fuel economy improvements of the future, the use of new technologies that reduce emissions associated with pavement overlay activity, but also reduce roughness at optimality, is paramount. For the same reason, technologies that provide more durable pavements are also encouraged.

# Table Of Contents

<b>TABLE OF CONTENTS .....</b>	<b>I</b>
<b>TABLE OF FIGURES.....</b>	<b>II</b>
<b>ACKNOWLEDGEMENTS .....</b>	<b>V</b>
<b>CHAPTER 1: INTRODUCTION.....</b>	<b>1</b>
1.1 RESEARCH PROBLEM .....	1
1.2 RESEARCH OBJECTIVES.....	3
1.3 RESEARCH SCOPE.....	4
<b>CHAPTER 2: LITERATURE REVIEW.....</b>	<b>6</b>
2.1 ROUGHNESS .....	6
2.2 GHG EMISSIONS AND COSTS ASSOCIATED WITH ROUGHNESS.....	7
2.3 GHG EMISSIONS AND COSTS ASSOCIATED WITH PAVEMENT OVERLAY APPLICATION .....	8
2.4 PAVEMENT ROUGHNESS PROGRESSION AND IMPROVEMENT MODELS .....	9
2.5 STATE OF THE ART IN OPTIMIZATION FOR REHABILITATION POLICIES.....	9
2.6 MARKET VALUE OF CARBON .....	10
2.7 CARBON DISCOUNTING.....	10
2.8 CARBON CREDITS .....	10
2.9 POLICY ANALYSIS.....	11
2.9.1 VMT Growth or Decay.....	11
2.9.2 CAFE Fleet Standards .....	11
2.9.3 New EPA Truck Standards.....	11
2.9.4 Natural Gas Emissions .....	11
2.9.5 New Pavement Technologies .....	11
<b>CHAPTER 3: METHODOLOGY.....</b>	<b>13</b>
3.1 OVERVIEW .....	13
3.2 OPTIMIZATION FRAMEWORK.....	14
3.3 PAVEMENT DETERIORATION AND IMPROVEMENT MODELS.....	15
3.4 AGENCY AND USER COSTS.....	16
3.5 AGENCY AND USER EMISSIONS.....	16
<b>CHAPTER 4: CASE STUDIES.....</b>	<b>18</b>
4.1 ASSUMPTIONS .....	18
4.2 I-80 RESULTS .....	21

4.2.1	<i>Decision Curve</i> .....	23
4.2.2	<i>Decision Curve Uses</i> .....	24
4.2.3	<i>Decision Curve Agency Perspective</i> .....	25
4.3	SR-13 RESULTS .....	27
4.4	SENSITIVITY ANALYSIS.....	29
4.4.1	<i>VMT Growth and Decline</i> .....	30
4.4.2	<i>Minimum Achievable Roughness</i> .....	34
4.4.3	<i>Deterioration Constant</i> .....	37
4.4.4	<i>Vehicle Fuel Economy</i> .....	41
4.4.5	<i>Overlay Emissions</i> .....	44
4.4.6	<i>Agency Costs</i> .....	45
4.4.7	<i>User Costs</i> .....	49
4.5	POLICY ANALYSIS OF EMISSION REDUCING STRATEGIES.....	52
4.5.1	<i>CAFE and Heavy Truck Standards in 2018</i> .....	52
4.5.2	<i>VMT Reduction Policy</i> .....	53
4.6	CASE STUDIES FINDINGS.....	54
<b>CHAPTER 5: DISCUSSION</b> .....		<b>58</b>
5.1	CONTRIBUTIONS.....	58
5.2	RECOMMENDATIONS FOR IMPLEMENTATION.....	59
5.3	LIMITATIONS.....	60
5.4	FUTURE WORK.....	61
5.5	CONCLUSIONS .....	61
<b>CHAPTER 6: REFERENCES</b> .....		<b>64</b>

## List of Figures

FIGURE 1:	GHG REDUCTIONS IN 2030, ALL SECTORS, FROM LUTSEY AND SPERLING (2009).....	4
FIGURE 2:	CARBON SOURCES ASSOCIATED WITH PAVEMENTS IN UNITS OF GLOBAL WARMING POTENTIAL FROM SANTERO AND HORVATH (2010). .....	5
FIGURE 3:	TYPICAL INTERNATIONAL ROUGHNESS INDEX (IRI) VALUES AS RE-PLOTTED FROM SAYERS ET AL. (1986). .....	7
FIGURE 4:	FUEL CONSUMPTION BY IRI FROM ZAABAR AND CHATTI (2010) WHERE ORIGINAL HDM- 4 MODEL (B) IS SHOWN WITH MODEL CALIBRATED FOR NORTH AMERICA (A). .....	8
FIGURE 5:	I-80 CO <sub>2</sub> E EMISSIONS TONNES/YR/KM DUE TO ROUGHNESS AND OVERLAY APPLICATION BY OVERLAY INTERVAL (YR). .....	22



FIGURE 6: I-80 TOTAL CO <sub>2</sub> E EMISSIONS TONNES/YR/KM AND TOTAL LIFE-CYCLE COSTS BY OVERLAY INTERVAL (YR). .....	23
FIGURE 7: I-80 DECISION CURVES FOR TOTAL LIFE-CYCLE COSTS BY CO <sub>2</sub> E EMISSIONS SHOWING COST EFFECTIVENESS OF POLICY CHANGE. ....	24
FIGURE 8: I-80 DECISION CURVES FOR TOTAL LIFE-CYCLE COSTS BY CO <sub>2</sub> E EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM) SHOWING MARKET VALUE OF CARBON ON PARETO FRONTIER. ....	25
FIGURE 9: I-80 DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). .....	27
FIGURE 10: SR-13 DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). .....	29
FIGURE 11: I-80 VMT GROWTH 3% ANNUALLY - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). ....	31
FIGURE 12: I-80 VMT GROWTH 1% ANNUALLY - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). ....	32
FIGURE 13: I-80 VMT DECLINE 1% ANNUALLY - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). ....	33
FIGURE 14: I-80 DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.0 (M/KM). .....	35
FIGURE 15: I-80 DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 2.0 (M/KM). .....	36
FIGURE 16: I-80 DETERIORATION RATE HALVED - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). ....	38
FIGURE 17: I-80 DETERIORATION RATE DOUBLED - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). ....	39
FIGURE 18: I-80 DETERIORATION REDUCED BY 20% - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). ....	40
FIGURE 19: I-80 FUEL ECONOMY HALVED - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). ....	42

FIGURE 20: I-80 FUEL ECONOMY DOUBLED - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). .....	43
FIGURE 21: I-80 OVERLAY EMISSIONS HALVED - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). .....	45
FIGURE 22: I-80 AGENCY COSTS HALVED - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). .....	47
FIGURE 23: I-80 AGENCY COSTS DOUBLED - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). .....	48
FIGURE 24: I-80 USER COSTS HALVED - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). .....	50
FIGURE 25: I-80 USER COSTS DOUBLED - DECISION CURVES FOR TOTAL, AGENCY, AND USER LIFE-CYCLE COSTS BY CO <sub>2</sub> EMISSIONS FOR ONE KILOMETER OF HIGHWAY AT MINIMUM ACHIEVABLE IRI = 1.5 (M/KM). .....	51
FIGURE 26: ILLUSTRATION OF OPTIMAL VALUE SHIFTS FROM SENSITIVITY ANALYSES .....	52
FIGURE 27: RESULTS FOR CAFE AND HEAVY-DUTY TRUCK STANDARDS FOR 2018. ....	53
FIGURE 28: RESULTS FOR VMT REDUCTION OF 1% PER YEAR. ....	54

## List of Tables

TABLE 1: USER COSTS NOT INCLUDING FUEL IN CENTS PER ADDITIONAL UNIT OF IRI PER KM OF PAVEMENT .....	21
TABLE 2: CASE STUDY DATA QUALITY ASSESSMENT.....	57

## Acknowledgments

I have had the good fortune of two co-advisors for this project. Although some may think having two advisors is a complication to avoid, my experience was exactly the opposite. Each advisor provided advice and guidance as expected but each on different aspects of the project. Thus, I gained the benefit of two great sets of valued input. And since each advisor has been more than generous in sharing the experiences and wielding their guidance, I feel more than doubly privileged. I truly have two role models for prioritizing graduate students to aspire to, two sets of skills to pass on to other graduate students, and two areas of expertise to bring forth in the form of curriculum. Thank you for all of your input, patience, and tireless responses to my queries Professor Arpad Horvath and Professor Samer Madanat. Your generosity and ceaseless giving has touched me to a depth I can only hope to aspire to.

I am honored to have Professor David Dowall and Professor Adib Kanafani, whom each have build illustrious and famous careers, serve on the dissertation committee. To have their names appear on this document is an honor I never expected. As this dissertation is among the last on earth to be graced by their signatures, I extend a heartfelt gratitude to them for their unparalleled experience, gracious input, and time spent on this project.

As members of my qualifying examination committee, Professor Alexander Skabardonis and Professor Joan Walker have each been cornerstones of my progress through the entire graduate program, each also serving on my written examination committee. I thank them both for their personal interest and guidance from the very beginning to the end. I must also thank Professor Mark Hansen and Professor Mike Cassidy for their consistent advice, also from the first day, as well as their continued support and interest in my progress. I would like to thank Professor Carlos Daganzo as chair of the admissions committee that brought me into the program and for the honor to learn from him directly the principles of traffic flow theory.

I would also like to thank Professor Susan Shaheen and Professor Timothy Lipman for their combined employment from the very first day I entered the graduate program and for their continued collaborations until the last day. It is my sincerest hope I can repay them or at least pass on their generosity and graciousness in the future. What I learned from them, the connections they allowed me, and with the graciousness they shared their careers, their knowledge, their success, and their private lives is simply immeasurable and I am truly humbled.

Always there for lunch, dinner, all meetings, and a better understanding of my research and exactly how it fits in the world than possibly anyone else on earth, was Professor Nakul Sathaye. I thank him for his friendship and vast knowledge he begrudgingly imparted with for this project.

Several fellow students stand out as having helped me throughout the program. Thanks go out to Joshua Pilachowski and Anthony Patire, whom answered my incessant questions and offered tireless advice. For fighting side by side in the trenches, I thank Lisa Zorn, and Julia Griswold. And to the students who entered the program with me and have remained friends I would like to thank Vikash, Karthik, Eleni, Ilgin, GKB, Weiwa, Robert, and Celeste.

My parents, Dr. William, Louise, and Naomi Lidicker have supported me greatly and without them I could not have achieved this goal. I thank you each for acting as role models thus

providing motivation for a doctorate at all, and for the social, emotional, and economic support to see the effort to completion.

Lastly, I would like to thank my partner Denise Morano for standing by me through two graduate programs, moving back and forth across the country, and being my friend and companion. You have truly empowered me to accomplish this goal.

This research was funded through the University of California Multi-campus Research Program on Sustainable Transportation and a fellowship from the University of California Transportation Center.

# 1 Introduction

The transportation sector is well-known to be a key aspect of climate change policy making (IPCC 2007). However, much of the focus of climate change and environmental emissions reduction has been on vehicle technologies and alternative fuel options (Lutsey and Sperling 2009). It has become increasingly apparent that pavement management decisions have a significant impact on environmental emissions as well (Santero and Horvath 2009, Sathaye et al. 2010). Since the 1980s, transportation infrastructure management has been a topic of importance due to the magnitude of agency expenditures and user costs (ASCE 2009). However, relatively little work has been conducted towards understanding the interrelationship between monetary costs and environmental emissions, and the potential for implementing policies which can simultaneously account for both concerns (Zhang et al. 2010a, 2010b).

This research takes a step towards the development of a more accurate understanding of the tradeoffs between greenhouse gas (GHG) emissions, in particular, and life-cycle costs in pavement management decisions. In particular, we analyze the single-facility optimal pavement resurfacing problem with simultaneous consideration for costs and GHG emissions due to both agency and users. Accordingly, we build on the single-facility pavement management methodology literature, while incorporating new data and methods to estimate GHG emissions. Although there are a myriad of environmental concerns associated with pavement management, we focus on the user-agency tradeoff between the effects of road roughness on fuel consumption and subsequent GHG emissions versus the GHG emissions attributable to pavement resurfacing.

The analytical framework developed in this study will afford the analysis of various climate change policies such as the new federal fuel economy standards, new EPA truck emission standards, demand management designed to reduce the vehicle miles traveled, or the use of natural gas in heavy trucks.

A pavement management “policy” is a technical term used in the asset management realm that refers to a pavement management strategy or prespecified plan to apply. For example, Caltrans uses the pavement management policy to apply an asphalt overlay on asphalt pavements whenever the pavement roughness value is beyond a value of 2.7 IRI (m/km) (Caltrans 2009). This policy or strategy is referred to as a threshold policy as the specified pavement roughness maximum or trigger roughness acts as a trigger for overlay activity.

Caltrans has an annual budget for state highway maintenance, which is divided up between the state’s nine districts. Each district allocates their share of the funds individually. In practice, the trigger roughness may not prompt overlay or rehabilitation activity, (as it should) as budgets are often below adequate levels. Thus, monies tend to be allocated to pavement segments in the worst condition or where politicians or administrators deem to be the highest priority. There is no current use of a formal pavement management system, which systematically optimizes the allocation of funds to a network such that resources such as monies produce maximum benefits.

## 1.1 Research Problem

In 2006, the then-governor of California, Arnold Schwarzenegger enacted the California Global Warming Solutions Act of 2006 to limit climate changing GHG emissions for the entire state to 1990 levels by the year 2020 (Assembly Bill No. 32, 2006). As California has 50,000

lane miles of state highways and 178 billion vehicle miles traveled (VMT) per annum (Caltrans 2007a), the question of how to manage these state pavements in a way that minimizes GHG emissions seems an obvious one to investigate. Methodologies for minimizing life-cycle costs had already been developed, but none for minimizing emissions in California (Carnahan et al. 1987, Friesz and Fernandez 1979, Golabi et al. 1982, Li and Madanat 2002, Ouyang and Madanat 2004, Ouyang and Madanat 2006, and Zhang et al. 2010a). As mentioned above, California has recently contracted for a PMS that minimizes costs to be implemented. Once the system is in place, the state stands to save a significant amount of the half a billion dollars spent annually on pavement rehabilitation (for 2007 and in 2007 U.S. dollars, Caltrans 2007a) (Golabi et al. 1982). However, as practical GHG emissions minimization methodologies for California have yet to be developed, there are no current plans for incorporating GHG emissions optimization into the proposed PMS system. Thus, this study's development of a pavement management optimization framework that provides decision makers with tradeoffs between the cost and the GHG emission optimalities is a critical step toward the state's climate change goals.

It is known that allowing pavements to progress to a poor condition causes vehicles traversing said pavements (users) to incur additional fuel consumption (Santero and Horvath 2009, Zhang et al. 2010a, Zaabar and Chatti 2010). This provides motivation to have all state highways in California to be freshly repaved as often as necessary to ensure no additional GHG emissions are created due to pavement roughness. However, repaving activity (asphalt overlay application) is associated with GHG emissions (Sathaye et al. 2010, Santero and Horvath 2009). We hypothesize that there exists an optimal pavement rehabilitation policy that will minimize GHG emissions similar to how optimal policy can minimize life-cycle costs. Further, that these points of optimality for costs and emissions do not necessarily reside at the same time.

This study quantifies the necessary input parameters, associates them with appropriate models, and determines a framework that will find both types of optimality. We compare the two optimality solutions with the goal of quantifying the trade-offs involved. We are interested in characterizing costs involved with saving GHG emissions due to the altering of pavement rehabilitation policy. Thus, we hope to quantify the trade-offs with respect to specific characteristics of specific California pavement segments.

The results of the analytical framework will produce information useful to decision makers in their quest to find the most appropriate methods to mitigate climate change. It is possible that pavement rehabilitation policy changes may or may not be an appropriate methodology for this goal. Additionally, by altering input parameters, other legislation or proposed government policies can be evaluated for their impact on the optimal costs and emissions for pavement rehabilitation strategy. For example, the newly enacted federal CAFE standards can be evaluated to see how improved vehicle fuel economy may alter the total emissions associated with pavements.

We expect that there will be situations where changes to the pavement management policy will result in reductions of both costs and GHG emissions. In these situations, decisions are trivial as there is no downside to improving both types of criteria. However, we also expect that there will be situations or a range of situations where a change in policy that reduces GHG emissions will increase costs, and vice versa. For these special situations, there is a give and take that decision makers will have to contemplate. In order to save some GHG emissions, how much money are the decision makers willing to spend? The amount depends on the goals of the decision makers and on who is paying the increased costs.

For example, if Caltrans spends more money on pavement rehabilitation activity, then the users of the roadways will save money and emit less GHG emissions as they will be using less fuel to travers smoother roads that have less rolling resistance. However, the increased costs for Caltrans and the increased GHG emissions associated with the pavement rehabilitation activities may outweigh the savings of the users. At any rate, there may be a point where an increase in Caltrans spending has a total reduction in GHG emissions, which would provide a benefit to society. On the other hand, if Caltrans wishes to save their own money and their own GHG emissions by reducing pavement rehabilitation activities, the cars and trucks that use the roadways will bare some additional costs due to traveling on rougher roads. These rougher roads will cause higher fuel consumption and more wear and tear on vehicles and cargo. If Caltrans will allow for the total GHG emissions to goes up, this will have a negative impact on climate change and human health.

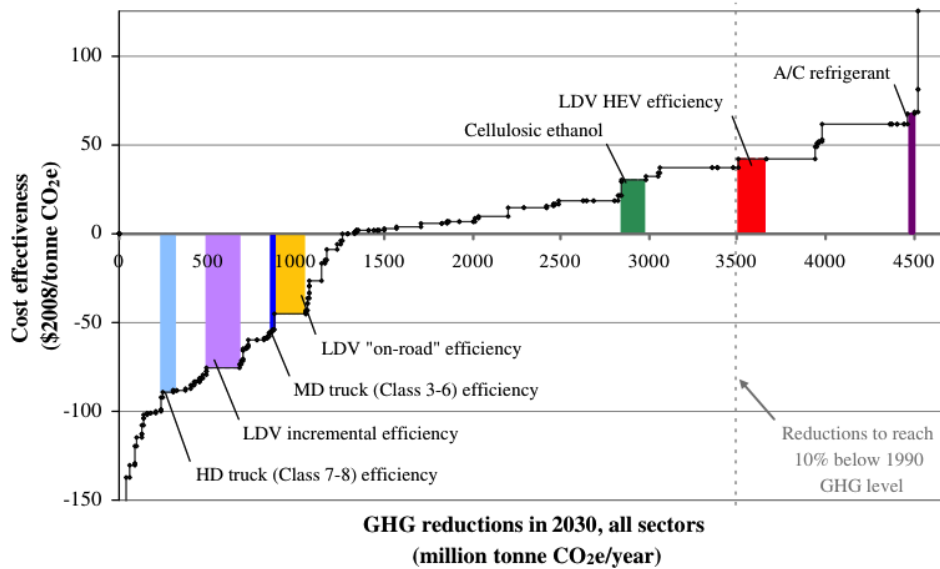
One thing is clear: an analytical framework that can illuminate exactly when and how these various pavement management policy changes will interact and who exactly is paying or emitting how much will greatly help decision makers wishing to accomplish their goals.

## ***1.2 Research Objectives***

One of the key goals of this research is to provide an analytical framework for optimizing roadway rehabilitation policy for GHG emissions in addition to the traditional costs. A result of the optimization process will be cost-effectiveness ratios in dollars per tonne of CO<sub>2</sub>e saved from any proposed or actual policy change. These cost-effectiveness ratios indicate exactly how much additional costs will be needed to save a unit of GHG emissions. Decision makers will be able to compare proposed rehabilitation policy changes intended to save emissions to other emission reducing strategies, such as insulating all public buildings. As an example, a plot of cost effectiveness ratios for various emission saving strategies is shown in Figure 1 (Lutsey and Sperling, 2009). If a market value for carbon were to exist, then this would identify a unique optimal roadway rehabilitation policy that optimizes both costs and emissions at the same time.

Additionally, estimated costs will be delineated by agency or DOT costs and pavement user costs. This will provide complete information for decision makers who wish to know how much additional cost, if any, will be born by users if the agency, such as Caltrans, decides to reduce their costs. Similar delineations will be provided for the GHG emissions.

Lastly, models developed in this research will allow for testing implications on roadway rehabilitation practices that governmental regulations or incentives may have. For example, this research investigates the effects of the new federal CAFE standards, VMT reduction strategies, new pavement materials technologies, and new pavement overlay technologies on roadway rehabilitation policies and their associated costs and emissions.



**Figure 1: GHG Reductions in 2030, All Sectors, from Lutsey and Sperling (2009).**

### 1.3 Research Scope

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

This research is centered on traditional hot-mix asphalt overlay applications. The terms rehabilitation or resurfacing can be used as synonyms for the process. Not included are minor maintenance activities such as crack sealing or patching. These activities are assumed to be accounted for in the overall deterioration model for the pavement. Also excluded from the analysis is complete pavement reconstruction, which involves capital expenditures, the complete removal and replacement of all asphalt, base, and sub-base of the pavement. Typically, replacement is done with more lanes or to a higher design standard (higher structural number). Newer pavement rehabilitation technologies such as warm-mix asphalt or cold-mix asphalt are considered in the sensitivity analysis.

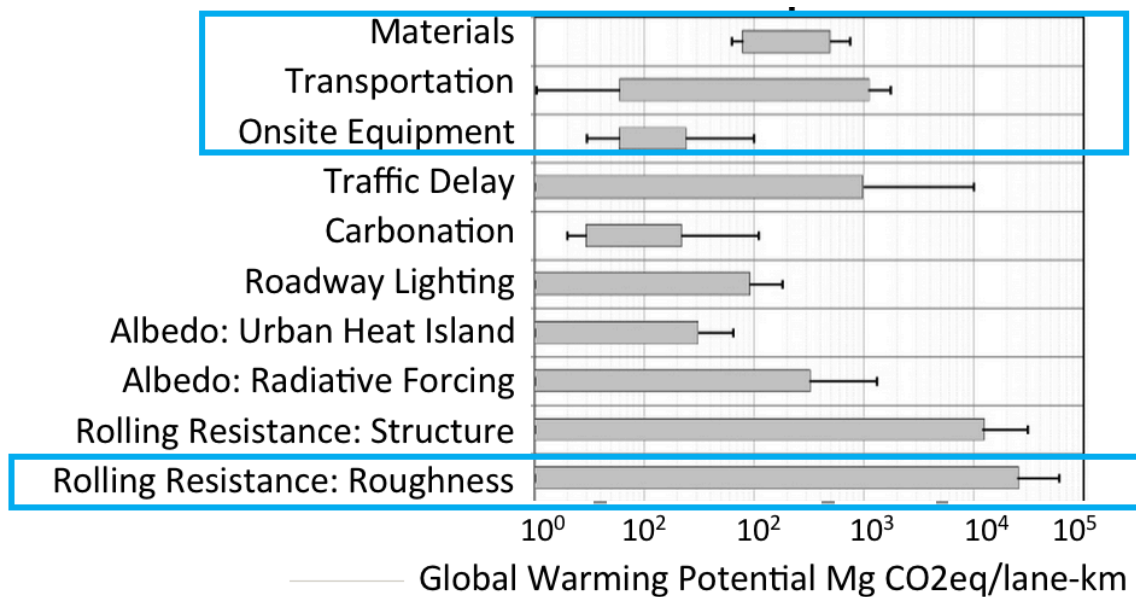
The temporal scope is for the year 2011 and all costs are expressed in 2011 U.S. dollars. Although many new pavement technologies are currently in use, the mainstay remains the hot-mix asphalt overlay. We aim to show the importance and effects of future implementation of new technologies as they relate to pavement rehabilitation strategy with a multi-objective optimization.

There are many carbon sources associated with pavements. A summary of various carbon sources and the magnitude of their contributions to the atmosphere is shown in Figure 2, which is reproduced from Santero and Horvath (2010). The metric is Global Warming Potential and the unit is one metric ton of CO<sub>2</sub> equivalent emissions per lane-km. Of interest is the



logarithmic scale of the axis and thus the large range of results. Of all the carbon sources shown, this research only includes those in the boxes (materials acquisition, materials transport, onsite equipment, and emissions due to pavement roughness).

Delays for traffic due to rehabilitation activity have been shown to have a non-trivial effect on emissions (Zhang et al. 2010a, Santero and Horvath 2011). However, for major metropolitan regions in California, Caltrans applies overlays exclusively at night specifically to mitigate this type of traffic delay. As additional fuel consumption for rerouting or delays is purely speculative at this time, this aspect of GHG emissions is not considered in this version of the study. Future iterations of the research will incorporate traffic delay for greater applicability.



**Figure 2: Carbon Sources Associated with Pavements in Units of Global Warming Potential from Santero and Horvath (2010).**

Of the various effects pavement roughness can have, this research includes the additional fuel usage of the pavement users, vehicle maintenance wear and tear, and the pavement deterioration rate. Excluded are the roughness effects on goods damage, vehicle speed, and comfort level. It has been established that roughness does affect speeds for heavy-duty vehicles (Watanatada, 1987). However, speeds only reduced above an IRI of approximately 4.0 m/km, which is above trigger roughness values in California and Arizona. Further, the analysis was performed on trucks with a top speed of approximately 72 km/h (45 mph), below which fuel consumption actually may increase making the effect of roughness more dramatic, not less.

## 2 Literature Review

In this section we discuss the previous literature related to pavement management and the environment. This discussion begins with a definition of pavement roughness and its effects on costs and GHG emissions for users. Then asphalt overlay costs and emissions for agencies are reviewed. We summarize pavement roughness progression models, which estimate the condition of a segment over time while the pavement improvement models, which estimate the rehabilitated condition of a road segment after the application of an overlay are presented. The current state of optimization for rehabilitation policies or strategies is reviewed before covering analytical issues for carbon, such as its market value, discounting, and credits. Lastly, backgrounds for various government policies and technologies are provided so that subsequent explorations are relevant.

This discussion is divided between road roughness and its effects on costs and GHG emissions, pavement supply-chain GHG emissions, and pavement deterioration and improvement models, all of which are components of the optimization methodology presented in Chapter 3.

### 2.1 *Roughness*

Road roughness is a measure of road surface irregularity or longitudinal profile in the wheel paths (Paterson 1987). Road roughness is defined: "...the deviations of a surface from a true planar surface with characteristic dimensions that affect vehicle dynamics, ride quality, dynamic loads and drainage" (American Society for Testing and Materials 1982).

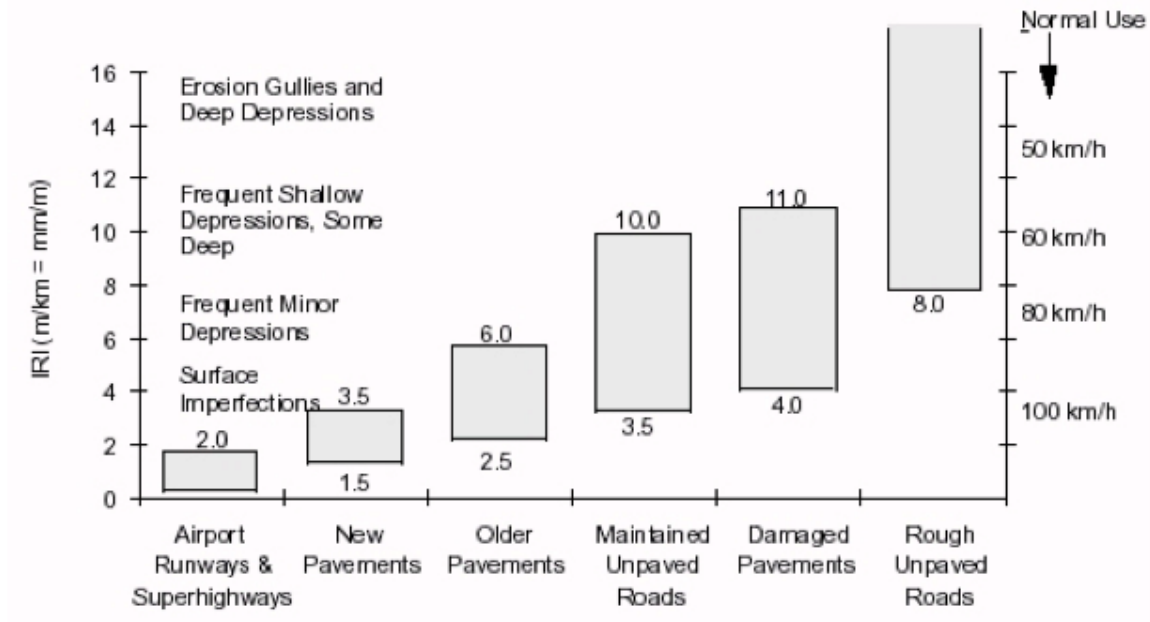
Roughness can affect vehicle performance, fuel consumption, vehicle wear, and thus vehicle handling, costs, safety, comfort, and speed of travel. In addition, roughness can affect surface drainage, dynamic loadings on the pavement, and thus the rate of deterioration (Paterson 1987, Watanatada 1987, Barnes and Langworthy 2004, Santero and Horvath 2009, Zaabar and Chatti 2010).

The typical maintenance activity to reduce roughness is application of an asphalt overlay. This may include milling the pavement prior to overlay application (Rajendran and Gambatese, 2007). Resurfacing is not synonymous with reconstruction, which consists of removing the entire original roadway and then replacing it with a new one.

Values of roughness can be expressed by the International Roughness Index (IRI) in units of meters of total vertical displacement per kilometer of travel distance (m/km). Another measure commonly used is the Quarter-car Index (QI, Maysmeter counts per km), where the metric  $IRI = QI/13$  for  $IRI < 17$  m/km (Paterson 1987). Many agencies use a maximum roughness or equivalently a "trigger roughness" to determine when an overlay should be applied. For example, the California Department of Transportation (Caltrans) uses a trigger roughness of 2.7 IRI (m/km) (Caltrans 2009), and the Arizona Department of Transportation uses 4.0 IRI (m/km) (Golabi et al. 1982).

From a national sample, the minimum initial IRI is approximately 0.5 m/km and a maximum of approximately 3.0 m/km. After ten years the minimum is 0.85 m/km and the maximum 3.8 m/km (Ksaibati and Mahmood, 2002). A non-U.S. source indicated new construction of paved roads can range from 1 to 4 m/km (poor construction), while gravel or

earth roads can range from 4 to 8 m/km (Paterson, 1987). Typical roughness values for runways to rough unpaved roads can be seen in Figure 3.

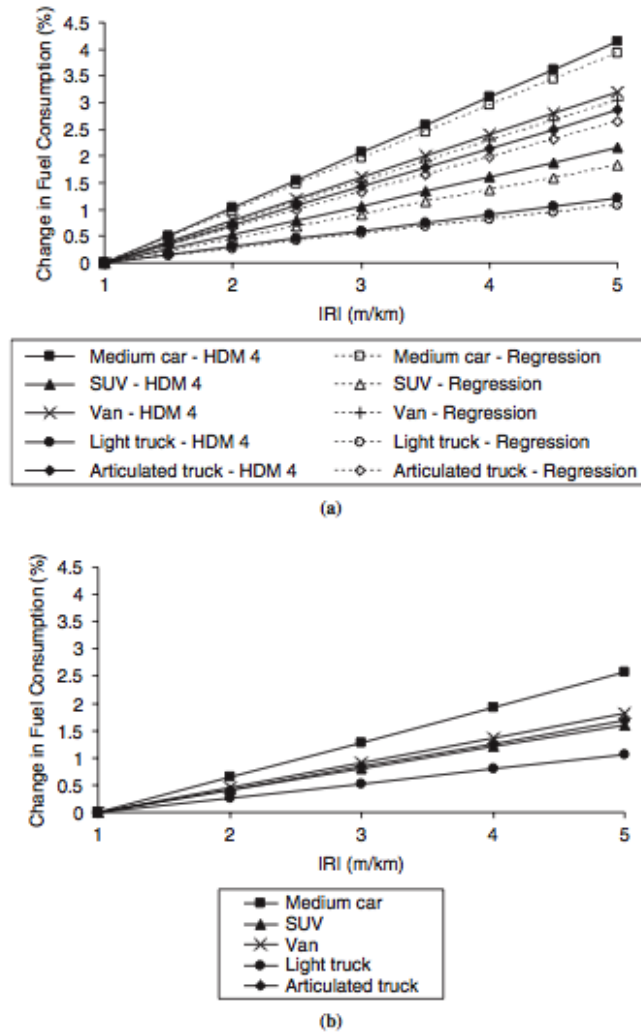


**Figure 3: Typical International Roughness Index (IRI) Values as Re-plotted from Sayers et al. (1986).**

## 2.2 GHG Emissions and Costs Associated with Roughness

The effects of roughness on fuel economy and costs has been quantified by several researchers (Watanatada 1987, Schuring 1988, and Zaabar and Chatti 2010). The Schuring (1988) study is motivated by the tire industry's analysis of rolling resistance due to various tire formulations. The work by Zaabar and Chatti (2010) takes the results of the Watanatada (1987) study and updates them with empirical data for North America in the 21<sup>st</sup> century. It is these estimates of the effect of roughness on fuel consumption that are adopted for this analysis and used in the case studies to estimate user fuel costs and GHG emissions due to roughness. A plot of their results is reproduced from the study in Figure 4. In the study, the heavy trucks were loaded with 21.32 metric tons of payload (47,000 lbs) and run a constant speed (speed limit). Notice the relations are linear, and that the largest trucks are affected by roughness less than some vehicles but more than others.

For non-fuel based user costs, the challenge is to find user costs as a function of pavement roughness. The Paterson (1987) study is a standard reference, but the age of the study and the fact that the costs are estimated in Brazilian Pesos makes application to California, over twenty years later, less than ideal. Barnes and Langworthy (2004) published a semi-meta analysis on this issue (semi-meta as some data are original). The non-fuel based user costs due to pavement roughness (maintenance/repair, tires, and depreciation) used in case studies are based on their results.



**Figure 4: Fuel Consumption by IRI from Zaabar and Chatti (2010) where Original HDM-4 Model (b) is Shown with Model Calibrated for North America (a).**

### 2.3 GHG Emissions and Costs Associated with Pavement Overlay Application

Typically, pavement roughness is repaired with an asphalt overlay application (Caltrans 2009). Estimates of GHG emissions attributable to pavement overlay application have been performed recently (Santero and Horvath 2009, Sathaye et al. 2010) and are directly applied in Section 4. Traditionally, costs for overlay application are provided in the form of dollars per lane distance, such as in the report on the State of the Pavement in California (Caltrans 2007a). However, for this study, costs delineated by thickness of the overlay are also required. Such information has been previously estimated by Small et al. (1989) and then adjusted in Section 4, using the Consumer Price Index, to 2011 U.S. dollars.

## ***2.4 Pavement Roughness Progression and Improvement Models***

Various models have been developed to predict pavement roughness progression (deterioration). Relevant deterioration models are those developed empirically by Paterson (1987), Tsunokawa and Schofer (1994), and Prozzi and Madanat (2004). While Prozzi and Madanat (2004) and Hong and Prozzi (2006) developed relevant models for North American highways, the demands of the data inputs transcend what is currently available for California. The Tsunokawa and Schofer (1994) model had no direct way to account for traffic loadings, which directly impact rates of deterioration and thus costs and emissions. The Paterson model explicitly accounts for both the design of the pavement (Structural Number) and the traffic loading (in Equivalent Single Axle Loadings or ESALs) and thus is the choice for this study as presented in Section 3. A pavement's Structural Number ( $N$ ) is determined by a linear combination of the thickness of the asphalt layer, the base layer, and the sub base layer ( $N = 0.44 \times \text{pavement thickness (in)} + 0.14 \times \text{base thickness} + 0.11 \times \text{sub-base thickness}$ , Small et al. 1989).

Pavement improvement functions predict the reduction in roughness resulting from the application of an overlay. Typically, the roughness improvement is a function of both the roughness at the time of overlay application and the thickness of the overlay. Two pavement improvement functions were considered for use in this study. The Ouyang and Madanat (2004) improvement function is empirically based on developing-country overlays that are too thin to reflect those used in North America. The Tsunokawa and Schofer (1994) improvement function, although not empirically based, better reflects thicknesses used in North America and is therefore employed for this study in Chapter 3.

## ***2.5 State of the Art in Optimization for Rehabilitation Policies***

Continuous pavement condition with rehabilitation activities is modeled by a saw-tooth curve as the pavement condition deteriorates over time but is periodically repaired. To avoid the discontinuities of the saw-tooth curve, Tsunokawa and Schofer (1994) used an average or trend line approximation technique to optimize resurfacing activity timing and intensity. Their pavement condition curve passed through the midpoints of the saw-tooth curve. Li and Madanat (2002) made use of their models but solved for an infinite time horizon and the fact that a steady state can be reached after the first resurfacing is performed, thus avoiding the use of a trend line though the saw-tooth curve midpoints. They found that an optimal resurfacing policy has the following characteristics: 1) the optimal policy can be expressed using a steady state roughness threshold structure, and 2) that if an overlay is to be applied that it be done so with the maximum intensity so as to improve the pavement to the minimum achievable roughness. Ouyang and Madanat (2006) applied calculus of variation based methods to solve a finite-horizon optimization process. Results were consistent with those found for the infinite horizon (Li and Madanat 2002).

Finally, a study by Gillespie and McGee (2007) added into the optimization process the additional fuel consumed by users due to roughness. They concluded that savings to users justified some additional investment by agencies in pavement quality. However, the study stops short of including emissions. Zhang et al. (2010a, 2010b) applied maintenance optimization to both emissions and costs for Michigan highways. They described a Pareto frontier for minimal emissions and costs, and provided example policy implications. However, the primary goal of the studies was a comparison of pavement materials. To this end, the studies included a limited

sensitivity analysis and the subsequent policy analyses do not consider Agency and User Costs separately.

This research expands upon the multi-criteria finite optimization concepts of Zhang et al. (2010a, 2010b), but more fully investigates the interrelationships of factors (such as the perspective of both User and Agency Costs) and includes more detailed policy analyses. We use a simpler deterioration model and a deterministic optimization approach based on Li and Madanat (2002). The simpler model provides insights into interrelations between factors and outcomes, which should be more valuable for policy and decision makers (Daganzo 2005, Sathaye and Madanat 2011).

## ***2.6 Market Value of Carbon***

There is no market value for carbon in North America at this time. There are up to 25 countries participating in cap-and-trade programs in other parts of the world. The value of carbon has been fluctuating along with the state of economies. One study attempted to estimate the value of carbon needed to capture the externalities associated with carbon and came to the conclusion that \$110/tonne of CO<sub>2</sub>e should do the trick (Knittel and Sandler 2011).

## ***2.7 Carbon Discounting***

Currently, the issue of whether to discount carbon, how to discount the carbon, and how much are hotly debated topics. For example, Cline (2004) argues that no discounting should be used for evaluating climate change policies. However, Hepburn (2006) makes several arguments for use of a small positive discount rate. Evaluations of several discounting schemes for carbon found problems with constant-rate discounting and their solution - declining discount rates - as small changes in assumptions resulted in large variations in outcomes by a factor of up to 40 (Guo et al. 2006). More recently, criticism of simply summing carbon over time for purposes of comparison have surfaced arguing that the time of release is critical and can change results of policy analysis (O'Hare et al. 2009, Kendal et al. 2009a, 2009b). For this study, we chose to not enter the large variation of options into the results so as to keep comparisons as simple as possible for maximum illumination of policy effects. Similarly, we chose to not utilize the new techniques of estimating total carbon that account for temporal differences. Thus, our study takes the conservative route of not discounting carbon over time.

## ***2.8 Carbon Credits***

Although no market for carbon exists at the federal level, the state of California has decided to launch a Carbon Cap-and-Trade program as of January 1, 2012. During the first year, a carbon tracking system will be tested until June, with the tracking becoming enforced starting in July. There will be two opportunities to trade carbon credits in this first year. On January 1, 2013, the carbon caps go into effect (CARB 2012) and large emitters in the state will have to own credits for each tonne of carbon they emit. The goal is to create a market for trading and regulating carbon emissions so that the total emissions of the state can be systematically lowered. This program is a key component of the California Global Warming Solutions Act of 2006 legislation (Assembly Bill No. 32, 2006). California will lead the rest of the United States with this legislation but is working closely with British Columbia, Quebec, and Manitoba through the Western Climate Initiative to develop complementary programs that will greatly widen the effectiveness of the California program.

## **2.9 Policy Analysis**

### **2.9.1 VMT Growth or Decay**

It is reasonable to assume traffic volumes will increase over time. Caltrans predicts a 1% annual growth rate for California (Caltrans 2007b). There are many situations where this may not happen such as in the event of implementation of new gas taxes or road pricing. A world wide economic depression could also cause VMT to stay stagnant or decline. To this end, a 3%, 1%, and -1% growth rate is applied to both the User Costs and User Emission estimates as well as the ESAL estimates used for the pavement deterioration model. The behavior and extent of VMT manipulation is evaluated in its effects on optimization of pavement rehabilitation policy and thus on pavement performance, total life-cycle costs, and GHG emissions.

### **2.9.2 CAFE Fleet Standards**

The federal Corporate Average Fuel Economy (CAFE) fleet standards were first enacted by the U.S. Congress in 1975. The program is administered by the National Highway Traffic Safety Administration and regulates the average fuel economy for fleet of cars and light trucks sold by each manufacturer. Recently, a new set of standards was enacted with four strata: two vehicle classes (passenger cars and light trucks) and two footprint sizes (smaller and larger) (EPA 2011). Specific average fuel economies are specified for each year for each vehicle class and footprint size until 2025. For example, the 2018 standards specify a CAFE of 5.2 L/100km (45 mpg) for small passenger cars, 6.9 L/100km (34 mpg) for larger passenger cars, 6.4 L/100km (37 mpg) for small light trucks, and 9.4 L/100km (25 mpg) for larger light trucks.

### **2.9.3 New EPA Truck Standards**

In October of 2010 the EPA announced the first-ever fuel economy and GHG emissions standards for medium and heavy-duty trucks in the U.S. Each class of heavy truck has a specified percent reduction in fuel consumption to be met by 2018 as compared to 2010 (New York Times, 2010).

### **2.9.4 Natural Gas Emissions**

Natural gas vehicles are widely believed to reduce CO<sub>2</sub>e emissions as compared to their traditional petroleum counterparts. However, the California Energy Commission estimates the “well-to-wheel” GHG emissions reduction to be approximately 20-30% for light-duty vehicles and for heavy-duty vehicles only 11-23%(CEC 2007). These estimates appear to be optimistic as another study by the Argonne National Laboratory estimated only a 17% reduction for light-duty vehicles and an increase of 5.7% for heavy-duty vehicles (DeLuchi 1991). However, the latter study points out that synthetic natural gas made from wood stock reduces emissions for light-duty vehicles by 55% and for heavy-duty vehicles by 44%.

### **2.9.5 New Pavement Technologies**

Many research efforts are underway to improve on pavement durability and effectiveness of overlay application. Often, these efforts focus on new materials (Zhang et al. 2010a), binders (Watson and Moore 2011), and even inserted structures (Cleveland et al. 2002). However, the

GHG emission impacts of such strategies are not well known. More typical pavement technology approaches to reducing GHG emissions center around the temperature the bitumen is heated to and using recycling methods (Miller and Bahia 2009).

The standard asphalt temperature method is referred to as hot mix asphalt (HMA) while techniques that use less energy and thus emit fewer GHG emissions are cold mix asphalt (CMA), half-warm mix asphalt (HWMA), and warm mix asphalt (WMA). Although these low-temperature processes require additional emulsions to either subsidize or replace bitumen, estimates indicate the additional energy and emissions to manufacture and transport these emulsions are far exceeded by the energy and associated emissions for heating bitumen in the HMA process (Slaughter 2004). From European practices, it was estimated that WMA processes may reduce CO<sub>2</sub> and SO<sub>2</sub> emissions by 30 – 40%, VOCs by 50%, CO by 10 – 30%, NO<sub>x</sub> by 60 – 70%, and particulate matter (PM) by 20 – 25% (Miller and Bahia 2009).

Another promising technique for reducing GHG emissions is by recycling the pavement materials during rehabilitation activity. Asphalt pavement is recycled almost 80% of the time in North America (Miller and Bahia 2009). However, the distance that new aggregate or processed asphalt must travel to the site has a large effect on the effectiveness of recycling to reduce energy consumption. Cold in-place recycling with foamed bitumen can reduce energy consumption by 20 – 50% (Thenoux et al. 2007). Just the recycling of materials, but still using HMA, may reduce the eco-burden (Eco-indicator 99) by 23% (Chiu et al. 2007). However, neither of these conclusions reflects GHG emissions reductions directly.



### 3 Methodology

This section provides a brief overview of the analytic process, and then defines the optimization framework and the specific functions and models used.

#### 3.1 Overview

Estimates for Total Costs, User Costs, and Agency Costs are calculated for relevant values of Overlay Interval. Corresponding Total GHG emissions are also estimated. These values are plotted with total emissions on the horizontal axis and costs on the vertical axis to produce decision curves. A portion of the curves correspond to the societal or agency Pareto optimal frontier, where Total Costs or Agency Costs and Total Emissions for these Overlay Interval values can be seen to represent non-dominated solutions. Accordingly, the decision curves contain information about the marginal costs in the form of Total Cost or Agency Cost per metric-ton (ton) of CO<sub>2</sub>e saved. Thus, comparisons to other GHG emission saving strategies can be made for integration into climate policy.

A basic premise of this study is that the costs and the emissions of the pavement overlay process should be offset by additional costs and emissions due to only pavement roughness, or lack of overlay application. It is important to recognize the distinction that not all costs and emissions of a vehicle traversing a pavement are counted against those of the overlay activity, just those due to pavement roughness. For example, a vehicle may use one gallon of gasoline to travel 30 miles on a highway, but only a small fraction of that gallon is used to overcome the roughness of the pavement and that small percentage is all that is tabulated in this study. The majority of the fuel used for the vehicle to overcome rolling friction and wind resistance is ignored.

The entire process is a melding together of established infinite time horizon optimization results and three sets of models: life-cycle cost models, emissions models, and pavement deterioration and improvement models. The difficulty with User Cost and Emissions estimates is the need for them to be a function of pavement roughness. Thus, when the term “User Costs” is used in the study, it refers explicitly to only those costs due to the pavement roughness. If there is no roughness, there are no User Costs. User Costs such as those for tires and vehicle wear and tear from roughness were found in the literature. Additional gasoline consumption due to only roughness is a linear relation also found in the literature. An average price for fuel in the U.S. for 2011 was used to estimate the component of User Costs due to additional fuel consumption from pavement roughness.

Agency Costs and Emissions are both a function of the asphalt overlay application intensity. Intensity refers to the thickness of the overlay. Thus, the thicker an overlay is, the higher the associated costs and emissions. Agency Costs are from previously published estimates, which are adjusted to 2011 dollars. The emissions models make use of LCA methodologies. The Agency Emissions estimates have been formulated from LCA studies by Sathaye et al. (2010), and Santero and Horvath (2009). As done for fuel consumption component of User Costs, User Emission estimates are converted directly from additional fuel consumption estimates due to pavement roughness only. No other User Emissions, such as those due to additional vehicle maintenance, are tabulated.

In order to estimate User Costs and Emissions accurately, the roughness of the pavement segment must be estimated for all times within an Overlay Interval time period. For this, an

empirical pavement roughness progression or deterioration model was employed. An exponential function of roughness with respect to time is calibrated for specific traffic loadings (ESALs) and pavement construction designs (structural number).

In order to estimate the Agency Costs and Emissions it is necessary to know the thickness of the asphalt overlay that is applied. For this an empirical pavement improvement model that is a function of the trigger roughness value (immediately prior to overlay application) and the minimum achievable roughness value (immediately after overlay application) estimates overlay thickness.

Simplifying results of prior infinite time horizon optimization methodologies allows for a collapsing of many decision variables to only one: Overlay Interval in years. As all cost and emission models are linear with respect to roughness and overlay thickness, the optimization process is guaranteed to have a global minimum for costs and another for emissions. The span of Overlay Intervals between the two different optimal rehabilitation policies creates a Pareto frontier of cost and emission estimates. Each Overlay Interval on this Pareto frontier is an optimal in that an improvement in one metric comes at the loss of the other. Quantifying this natural phenomenon is the goal of this research. A policy change that saves emissions will have an associated cost. Thus, a cost-effectiveness value can be estimated for any proposed change in policy (\$/tonne CO<sub>2</sub>e saved). In this way, comparisons can be made to other emission saving strategies, such as low carbon fuel standards. Outside the Pareto frontier, the cost of saving emissions is negative or will also save costs. Thus, decisions are trivial outside the Pareto frontier. Results are generated to include the Pareto frontier and also time intervals beyond the Pareto subsection, and thus plots of results are referred to as Decision Curves instead of Pareto curves. The specifics of this process are detailed in the following section.

### 3.2 Optimization Framework

The objective is to minimize the net present value of the life-cycle costs for agency and users (Equation 1), subject to specific constraints (Equation 2).

$$\text{Min } V = \sum_{n=1}^{\infty} \left\{ \int_{t_{n-1}}^{t_n} C(s(t)) e^{-rt} dt + M(w_n) e^{-rt_{n-1}} \right\} \quad (1)$$

s.t.

$$\begin{aligned} s_n^- - s_n^+ &= G(w_n, s_n^-), \\ s(0) &= s^+, \end{aligned} \quad (2)$$

where  $V$  is the present value of Agency and User Cost over an infinite horizon (U.S. \$),  $t_n$  the time of the  $n$ th resurfacing,  $s(t)$  the pavement roughness as a function of time,  $C(s(t))$  the User Cost rate as a function of pavement roughness,  $w_n$  the intensity (thickness) of the  $n$ th resurfacing,  $M(w_n)$  the Agency Cost as a function of resurfacing intensity,  $r$  the discount rate, and  $G(w_n, s_n^-)$  is the improvement in pavement condition (from trigger roughness  $s^-$  to minimum achievable IRI or initial roughness  $s^+$ ) as a function of resurfacing intensity and pavement roughness prior to resurfacing (trigger roughness). Note the Agency Costs  $M$  are discounted at the beginning of the Overlay Interval as the costs are attributed to the subsequent years of effect (Li and Madanat 2002, Ouyang and Madanat 2004, Sathaye and Madanat 2011).

The decision variables are Overlay Interval  $\tau_n = t_n - t_{n-1}$  and overlay thickness  $w_n$ . Although, as previously mentioned in Section 2, the approach in this paper is more straightforward than prior work, these decision variables account for the same policy options (Golabi et al. 1982, Zhang et al. 2010a, 2010b). Specifically, by allowing the Overlay Interval to vary, the discrete annual pavement treatment option to do nothing is accounted for. By allowing the overlay thickness to vary, the discrete treatments of varying intensity are accounted for. However, using the steady state methodology of Li and Madanat (2002), we can simplify to  $\tau_n = t_n - t_{n-1} = \tau, \forall n$ , and  $w_n = w, \forall n$ . This steady state simplification is based on the fact that the system enters a steady state at the time of the first pavement resurfacing (regardless of pavement initial roughness as long as initial roughness is less than steady state trigger roughness). Thus, after accounting for  $k$  different types of vehicles (cars, trucks, etc.) with their own associated costs and emissions, the problem can be optimized by finding the minimum equivalent annualized value of the infinite life-cycle costs, as shown in Equations 3 and 4 (Au and Au 1992).

$$\text{Min } \frac{\sum_{k=1}^K \left\{ \int_0^{\tau} C_k(s(t)) e^{-rt} dt \right\} + M(w)}{1 - e^{-r\tau}} (e^r - 1) \quad (3)$$

s.t.

$$\begin{aligned} s^- - s^+ &= G(w, s^-), \\ s(0) &= s^+, \end{aligned} \quad (4)$$

where  $C_k$  is now the User Cost rate for vehicle type  $k$ .

Similarly, since emissions are not discounted over time (see Section: Carbon Discounting in Chapter 2), optimizing for emissions uses the annualized functional form shown in Equations 5 and 6.

$$\text{Min } \frac{\sum_{k=1}^K \left\{ \int_0^{\tau} E_k(s(t)) dt \right\} + A(w)}{\tau} \quad (5)$$

s.t.

$$\begin{aligned} s^- - s^+ &= G(w, s^-), \\ s(0) &= s^+, \end{aligned} \quad (6)$$

where  $E_k(s(t))$  is the User Emissions rate, and  $A(w)$  is the Agency Emissions as a function of overlay thickness.

### 3.3 Pavement Deterioration and Improvement Models

The pavement deterioration model (Paterson 1987) is shown in Equation 7.

$$s(t) = [s^+ + \alpha(1 + N)^q l(t)] \exp(\beta t), \quad (7)$$

where  $s(t)$  and  $s^+ =$  Roughness in m/km at time  $t$  and  $t=0$ , respectively,  $l(t)$  = the cumulative ESALs until time  $t$  in units of million ESALs/lane,  $t$  = number of years since the last overlay, and  $N$  = the structural design number of the pavement segment, and  $\alpha, \beta, q$  are constants.

The pavement improvement function (Li and Madanat 2002) is shown in Equation 8.

$$G(w, s^-) = g_1 \sqrt{w} + g_2 s^- + g_3, \quad (8)$$

where  $w$  is the overlay thickness (mm),  $s^-$  is the roughness value at time immediately prior to overlay application (QI), and all  $g_1, g_2, g_3$  are constants. Thus, solving  $G = s^- - s^+$  for  $w$ , we derive Equation 9.

$$w = \left[ \frac{(1 - g_2)s^- - s^+ - g_3}{g_1} \right]^2, \quad (9)$$

where  $s^+$  is the roughness after the application of the overlay (minimum achievable IRI) and  $s^-$  is the roughness just prior to overlay application (trigger roughness). Recall that Li and Madanat (2002) found for life-cycle cost minimization that the optimal strategy is to resurface each time to the best state achievable (minimum achievable IRI). This finding can be similarly applied to the GHG emissions minimization process as both the life-cycle cost and GHG emission functions are linear in the same variables, and thus the same optimizations hold. Furthermore, since  $s^-$  is a function of  $t$ , all dependent variables can be solved for as a function of Overlay Interval  $\tau$ . Thus,  $\tau$ , which can be equivalently expressed as a trigger roughness, becomes the sole decision variable.

### 3.4 Agency and User Costs

The cost estimates are based on linear functions (Li and Madanat 2002, Ouyang and Madanat 2004, Sathaye and Madanat 2011). For User Costs, the value of the constants includes the amount of additional fuel used due to only pavement roughness multiplied by the current price of the fuel. The User Costs are a function of pavement roughness  $s(t)$ , while the Agency Costs are a function of the applied overlay thickness  $w$ .

Thus, the functions are given by Equations 10 and 11.

$$C_k(s) = c_k(s - s^+), \quad (10)$$

where  $C_k(s)$  is the User Cost rate function,  $s - s^+$  is the change in roughness from the minimum achievable IRI, and the  $c_k$  is constant for each vehicle type  $k$ .

$$M(w) = mw + n, \quad (11)$$

where  $M(w)$  is the Agency Cost function,  $w$  is the overlay thickness, and  $m, n$  are constants.

### 3.5 Agency and User Emissions

Zaabar and Chatti (2010) updated the emissions models from Wantanatada et al. (1987) for application to North America. The effects of roughness on fuel consumption for several types of vehicles are provided. They indicate a linear relation between roughness and change in fuel consumption. Also assumed is the initial or minimum achievable pavement roughness. Each subsequent year has an estimated roughness increase and associated additional fuel requirements. The additional fuel is summed over the overlay period, and converted to GHG emissions ( $\text{CO}_2$ ) for one kilometer of travel by virtue of an EPA constant based on volume of fuel (EPA 2005). To approximate the GHG emissions due to fuel extraction, refining, and transportation, a well-to-pump factor of 1.18 is applied to the fuel (based on an average 85% fuel production efficiency from Wang 2002, and Chester and Horvath 2009).

The emissions due to pavement overlay application are estimated from a linear relation to the number of lanes at the representative section of roadway and the overlay thickness applied.

An emission factor per 1.6 km per lane per 7.6 cm overlay (per mile per lane per three-inch overlay) has been estimated by Sathaye et al. (2010).

The equations that describe the emissions are analogous to those for costs. Agency Emissions are a function of overlay thickness, and User Emissions are a function of pavement roughness change.

Thus, the functions are given by Equation 12 and 13.

$$E_k(s) = e_k(s - s^+), \quad (12)$$

where  $E_k(s)$  is the User Emission rate function,  $s - s^+$  is the change in roughness from the minimum achievable IRI, and the  $e_k$  is constant for each vehicle type  $k$ .

$$A(w) = aw + b, \quad (13)$$

where  $A(w)$  is the Agency Emissions function,  $w$  is the overlay thickness, and  $a, b$  are constants.

## 4 Case Studies

In this section, two California case studies are investigated, using the developed analytical framework, as base cases. First the assumptions and input parameters are presented and then the results and their uses. Next, a sensitivity analysis is performed to assess parameter input uncertainty implications as well as potential policies that coincide with these input parameter variations. Lastly, by adjusting the input parameters again, the analytical framework is applied as an example, to two emissions-reducing policies. The first policy is a set of two actual policies that combine for investigating the effects of the new federal CAFE standards for the year 2018 along with the new federal heavy-duty truck emission and fuel economy standards, also for the year 2018. The second policy is hypothetical, and represents a case where a new fuel tax, road-pricing scheme, or other demand management policy, such as land use changes, will reduce traffic loadings by 1% annually.

The goal of these exercises is first to test the analytical framework for feasibility and practicality of its output, second to gain insights into total life-cycle costs and GHG emissions tradeoffs, and lastly to gain insights on the effects of input parameter uncertainty and related politically-motivated policy changes.

Optimal Overlay Intervals for two case pavement segments in California's San Francisco Bay Area are computed for both criteria. One represents a major highway segment with high volume traffic commuting to and from San Francisco and the other a surface street arterial with relatively light traffic. Evidence suggests optimal maintenance practices may not be the same for each segment type (Muench et al., 2007). As this research is an extension of prior research on pavement-associated emissions, case studies are based on the reference (Sathaye et al. 2010) and new analyses are completed. For the case of the major highway with high volume traffic, a complete sensitivity analysis is performed. Each input parameter is varied systematically to test the outcomes for their sensitivity to each parameter. For both the major highway with high traffic volumes and the smaller surface street with relatively low traffic, two politically-motivated policy changes will be analyzed. This will show how these actual or hypothetical policy changes will affect the pavement management outcomes as well as how changes affect the smaller roadway relative to a larger roadway.

### 4.1 Assumptions

Below is a list of the assumptions used for the case study analyses.

#### **Pavement and Loads**

The scenarios from Sathaye et al. (2010) are extended. They are an interstate segment of I-80 close to the Bay Bridge in the San Francisco Bay Area (near the SR-13 junction), and the nearby SR-13, an arterial surface street segment (near the SR-123 junction). The I-80 segment is ten lanes wide (in two directions), and the SR-13 segment is two lanes wide (in two directions). For the I-80 segment, only the truck (far right) lane has any effect on fuel consumption due to roughness (as the truck lane deteriorates the fastest). Additionally, as per the California Highway Design Manual (Caltrans 2009), 80% of trucks are assumed to travel in the far right lane.

From Paterson (1987), the deterioration model constant parameter values are  $\alpha = 725$ ,  $\beta = 0.0153$ , and  $q = -4.99$ . From Sathaye et al. (2010), we have the Structural Number  $N$  and Equivalent Single Axle Load  $l(t)$  estimates for both the I-80 and SR-13 segments ( $N = 5.721$  and

3.28,  $l(t) = 0.98112$  and  $0.017885$  million ESALS, respectively). The pavement improvement function constant parameter values are  $g_1 = 5$ ,  $g_2 = 0.78$  and  $g_3 = -66$  (Tsunokawa and Schofer, 1994). The minimum or best achievable roughness for our base case scenario is  $IRI = 1.5$  (m/km).

## **Traffic Volumes**

The traffic loading assumptions were obtained from the Caltrans Report on Truck Annual Average Daily Traffic 2008 (Caltrans 2008). For the I-80 segment, we assume an annual average daily traffic (AADT, two-way traffic) of 273,000 light-duty vehicles (Light Vehicles) and 13,131 heavy-duty vehicles (Heavy Vehicles). For the SR-13 segment, we assume an AADT of 25,000 Light Vehicles and 481 Heavy Vehicles.

## **Vehicle Fuel Economy**

The Light Vehicles are assumed to have an average fuel economy of 10.2 L/100km (23 mpg) (Bureau of Transportation Statistics 2006, Sperling and Gordon 2009). The Heavy Vehicles are assumed, due to the existence of empty and not fully laden loads and an average fleet distribution, to consume fuel at a rate of 33.6 L/100km (7 mpg) (Barnes and Langworthy 2004).

For the sensitivity analysis the new CAFE standards in conjunction with the new heavy truck emission standards set by the EPA are used. Since the heavy truck regulations are set for 2018, the CAFE standards for that same year are used. It is unfortunate that the fleet average fuel economy used for the analysis is assumed to be the amount of the regulation, which is unrealistic. However, this assumption was adopted as estimating the fleet turnover rates and associated vehicle age distributions was beyond the scope of this study. Thus, this analysis represents an upper bound. It was also assumed that the distribution of VMT between “smaller” and “larger” footprint passenger cars and light trucks each approximates a 50-50 split. Further it was estimated that there are approximately two passenger cars for each light truck contributing to the national VMT estimates (Bureau of Transportation Statistics 2011a, 2011b). This works out to an average fuel economy for passenger cars of 6.4 L/100km (36.7 mpg).

The EPA heavy truck emission standards are expressed as percent reductions as compared to the year 2010. A different reduction is specified for several heavy truck classes. Thus, the new heavy truck average fuel economy is the weighted average of the number of each class of heavy truck on the particular pavement segment (Caltrans 2008) and their respective new regulated fuel economies. For the I-80 segment, this works out to 28.3 L/100km (8.3 mpg), and for SR-13 it is 29.4 L/100km (8.0 mpg).

Also considered is the scenario where passenger and light truck CAFE standards are considered for the year 2025 in conjunction with the scenario that all heavy trucks have been switched over to natural gas fuel by federal mandate. In this way, the fuel economy of the fleet is approximately doubled.

## User and Agency Emissions

The effect of a unit of additional roughness ( $IRI = 1 \text{ m/km}$ ) on user fuel consumption was empirically estimated by Zaabar and Chatti (2010). For Light Vehicles, a one percent change in IRI implies a 1.05% change in fuel economy. For Heavy Vehicles, a one percent change in IRI implies a 0.725% change in fuel economy. Using these fuel consumption estimates in combination with EPA estimates of  $\text{CO}_2$  emissions per unit of fuel (EPA 2005), the User Emission estimates are calculated. The EPA estimates that for Light Vehicles that use gasoline, there are 2.32 kg  $\text{CO}_2$  emitted per liter of fuel. For Heavy Vehicles that use diesel, there are 2.67 kg  $\text{CO}_2$  emitted per liter of fuel. After accounting for supply chain emissions of these fuels (Wang 2002, Chester and Horvath 2009), the emission rates become 2.7 kg  $\text{CO}_2/\text{L}$  of gasoline and 3.1 kg  $\text{CO}_2/\text{L}$  of diesel.

Agency Emissions are approximately 45,000 kg  $\text{CO}_2\text{e}$  per two-lane kilometer per cm thickness of asphalt overlay applied (Sathaye et al. 2010).

Currently, the issue of whether to discount carbon, how to discount the carbon, and how much are hotly debated topics. For example, Cline (2004) argues that no discounting should be used for evaluating climate change policies. However, Hepburn (2006) makes several arguments for use of a small positive discount rate. Evaluations of several discounting schemes for carbon found problems with constant rate discounting and their solution - declining discount rates - as small changes in assumptions resulted in large variations in outcomes by a factor of up to 40 (Guo et al. 2006). More recently, criticism of simply summing carbon over time for purposes of comparison have surfaced arguing that the time of release is critical and can change results of policy analysis (O'Hare et al. 2009, Kendal et al. 2009a, 2009b). For this study, we chose to not enter the large variation of options into the results so as to keep comparisons as simple as possible for maximum illumination of policy effects. Similarly, we chose to not utilize the new techniques of estimating total carbon that account for temporal differences. Thus, our study takes the conservative route of not discounting carbon over time.

## User and Agency Costs

As noted above, the Agency Costs have both a constant and a variable component (Equation 5). The Agency Costs from Table 3.1 of Small et al. (1989) for both components have been converted to 2011 dollars using the CPI factor of 2.39 to \$5,600/lane-km/cm of overlay, and \$251,000/lane-km of pavement for Urban Interstates, or \$196,000/lane-km for Urban Minor Arterials. The overlay costs per centimeter of thickness is additionally divided by 0.44 to adjust from units of durability to inches (2.27 inches of asphalt per unit of durability) and then converted to centimeters.

The User Costs due only to roughness (excluding fuel) come from Barnes and Langworthy (2004). They provide operating costs for two different pavement roughness values (one very smooth and one very rough). From these values, costs per unit of roughness were derived (excluding fuel). The results are shown in US cents per additional unit of IRI per km of pavement in Table 1.

Fuel costs are estimated from the assumed vehicle fuel economy along with the assumed effect of roughness on fuel economy. Thus, the final fuel consumption is multiplied by the price of fuel, and added to the non-fuel User Costs from Table 1 to obtain parameter  $c_k$  for Equation 10 (User Costs non-fuel/IRI + User Costs of fuel/IRI = Total User Costs/IRI). The fuel prices used



for California are \$0.91/L (\$3.45/gal) of gasoline, and \$0.99/L (\$3.75/gal) of diesel (Energy Information Administration 2011).

All costs are discounted at the rate of 4% and calculated over an infinite time horizon (Caltrans 2007b).

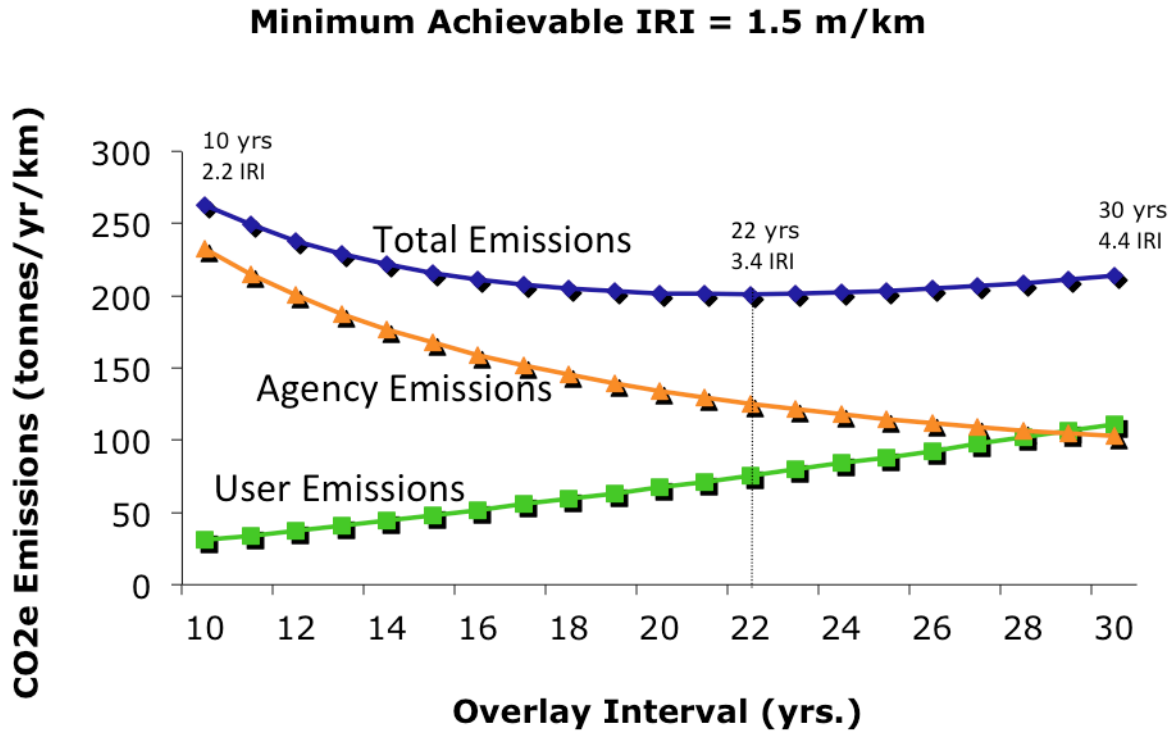
**Table 1: User Costs not including fuel in cents per additional unit of IRI per km of pavement**

Category	Automobile	SUV/Pickup	Commercial Truck
Total Marginal Costs	0.067	0.072	0.142
Maint/Repair	0.021	0.014	0.067
Tires	0.005	0.005	0.014
Depreciation	0.041	0.043	0.052

Source: Barnes and Langworthy 2004

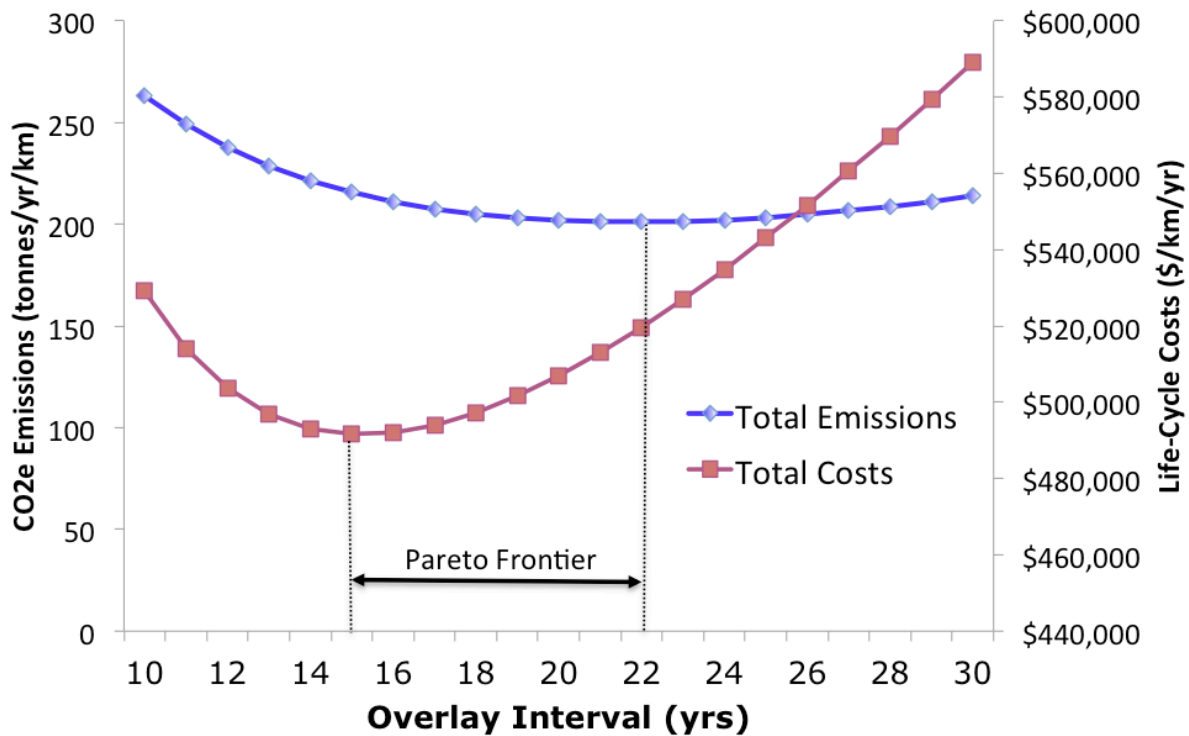
## **4.2 I-80 Results**

For the case of I-80 with initial pavement roughness of 1.5 IRI (m/km), the tradeoff between CO<sub>2</sub> emissions due to overlays and those due to roughness is shown in Figure 5. This figure shows how I-80 overlay emissions decrease as overlays are applied less often, but emissions due to roughness and the associated lower fuel economies increase. For this case, the Overlay Interval that minimizes the Total CO<sub>2</sub> emissions is 22 years corresponding to a trigger IRI of 3.4 m/km. This trigger roughness is almost exactly in between the California trigger roughness of 2.7 IRI and Arizona's 4.0 IRI. Agency Emissions dominate for Overlay Intervals lower than 28 years, while User Emissions dominate for Overlay Intervals above 28 years. Thus, for this case, most of the emissions come from the agency overlay efforts.



**Figure 5: I-80 CO<sub>2</sub>e Emissions tonnes/yr/km Due to Roughness and Overlay Application by Overlay Interval (yr).**

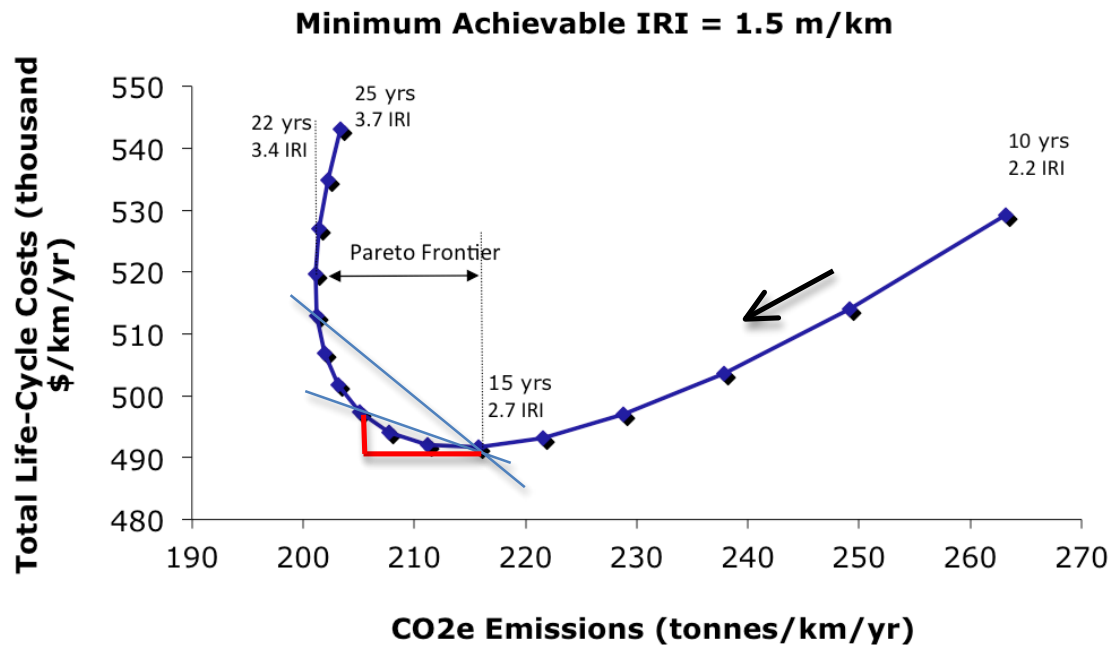
To illustrate how these emissions interact with costs, the Total Emissions curve is reproduced but with the Total (Life-cycle) Costs curve superimposed (Figure 6). One can see that the Total Cost minimum occurs when the Overlay Interval is 15 years, while the Total Emissions minimum is 22 years. A Pareto frontier of optimal rehabilitation policies lies on the sub-interval between these two different optimal Overlay Intervals. For within this sub-interval, if a policy change is enacted to reduce Total Costs (e.g. change from Overlay Interval of 20 years to 19 years), then Total Emissions must increase. Similarly, if a policy change reduces Total Emissions, then Total Cost must increase. However, outside this Pareto frontier sub-interval, any policy change that reduces one criterion also reduces the other and thus decisions are trivial.



**Figure 6: I-80 Total CO<sub>2</sub>e Emissions tonnes/yr/km and Total Life-cycle Costs by Overlay Interval (yr).**

#### 4.2.1 Decision Curve

A more traditional perspective of the Pareto frontier is that where the Overlay Interval axis is removed and the emissions are directly juxtapositioned against the costs. This is the case in Figure 7 where the horizontal axis represents the Total Emissions, while the vertical axis is the life-cycle Total Costs. The Overlay Intervals are now indicated by values placed on the curve itself along with the equivalent Trigger Roughness values. The arrow along the curve indicates the direction of increasing Overlay Interval. Again, the Pareto frontier is depicted between the Total Cost and the Total Emissions minimums of 15 and 22 year Overlay Intervals, respectively. The Total Cost optimal corresponds to a Trigger Roughness of 2.7 IRI, which coincidentally is the California value. Since the depicted curve includes more than just the Pareto frontier, it will be referred to as a Decision Curve.



**Figure 7: I-80 Decision Curves for Total Life-cycle Costs by CO<sub>2</sub>e Emissions Showing Cost Effectiveness of Policy Change.**

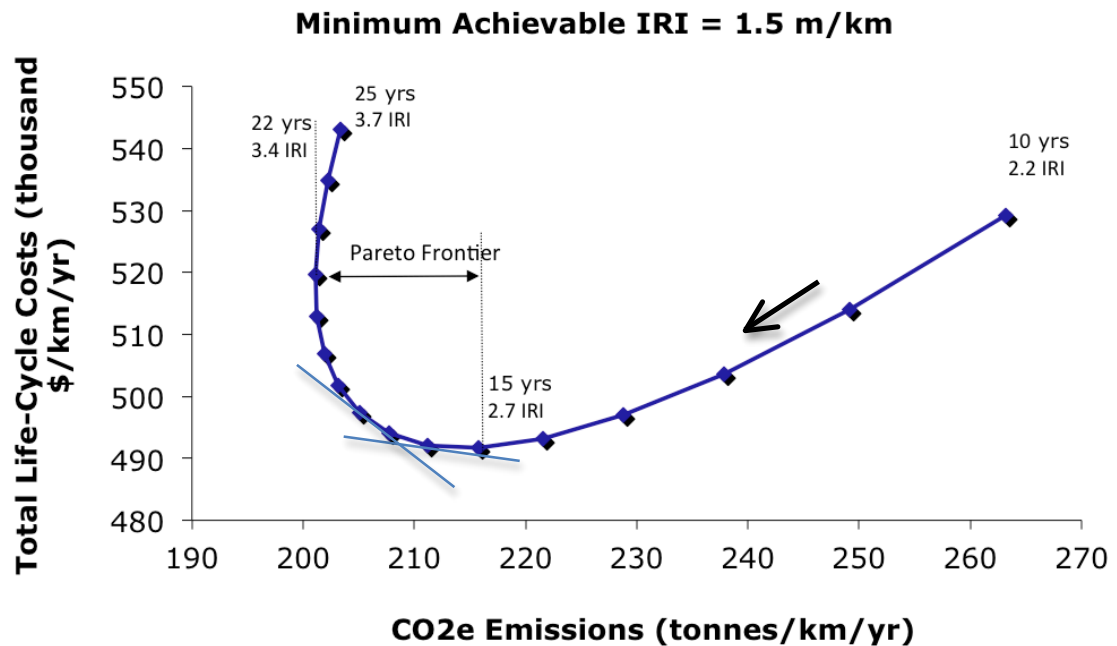
#### 4.2.2 Decision Curve Uses

The Decision Curve indicates for decision makers both minima for optimal pavement resurfacing policy by either criterion. In addition the curve indicates the cost-effectiveness for a proposed change in policy. For example, a change from a ten-year Overlay Interval to 15 years will reduce both Total Costs and Total Emissions bringing the Total Costs to a minimum. However, if Caltrans is already making use of their official Trigger Roughness and they wish to reduce emissions, a change from the 15-year Overlay Interval to 18-years will save the amount of Total Emissions indicated by the horizontal red line segment, but incur additional Total Costs indicated by the vertical red line segment. Thus, the associated secant line has a slope that is the negative of the cost-effectiveness of such a policy change (\$/tonne CO<sub>2</sub>e saved). For the example shown, the cost to save some emissions is approximately \$500/tonne of CO<sub>2</sub>e saved. It is important to note that if it is desired to save more emissions, the slope increases and thus the cost per unit of emissions saved increases. Now that it is possible to determine the \$/tonne of CO<sub>2</sub>e saved for any proposed pavement rehabilitation policy change, the value can be used to compare other emission mitigation strategies (such as retroactively insulating all public buildings).

The curve can also be used to identify the optimal overlay interval from an economic efficiency perspective. If a market value for CO<sub>2</sub> exists, then one simply moves along the curve until the point where the negative of the slope of tangent to the curve is equal to the market value; this point indicates the market optimal Overlay Interval (Figure 8). Since points along the Pareto frontier span zero \$/tonne CO<sub>2</sub>e saved (cost optimal) to infinite \$/tonne CO<sub>2</sub>e (emissions optimal), any market value for carbon is guaranteed to exist. For example, if we assume CO<sub>2</sub> to have the value \$110/tonne (Knittel and Sandler 2011), for this particular case this corresponds to

an Overlay Interval of approximately 15.5 years. For lower values of carbon, the cost minimum is essentially the optimal.

It should be pointed out, however, that at the \$110/ton point, only 3.5 tons of CO<sub>2</sub>e is being saved per year per km and at the cost optimal, no CO<sub>2</sub>e is being saved. At the \$500/tonne point mentioned earlier, almost 11 tons of CO<sub>2</sub>e are being saved per year per km. As the cost per ton increases, so does the potential emission savings.



**Figure 8: I-80 Decision Curves for Total Life-cycle Costs by CO<sub>2</sub>e Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km) Showing Market Value of Carbon on Pareto Frontier.**

#### 4.2.3 Decision Curve Agency Perspective

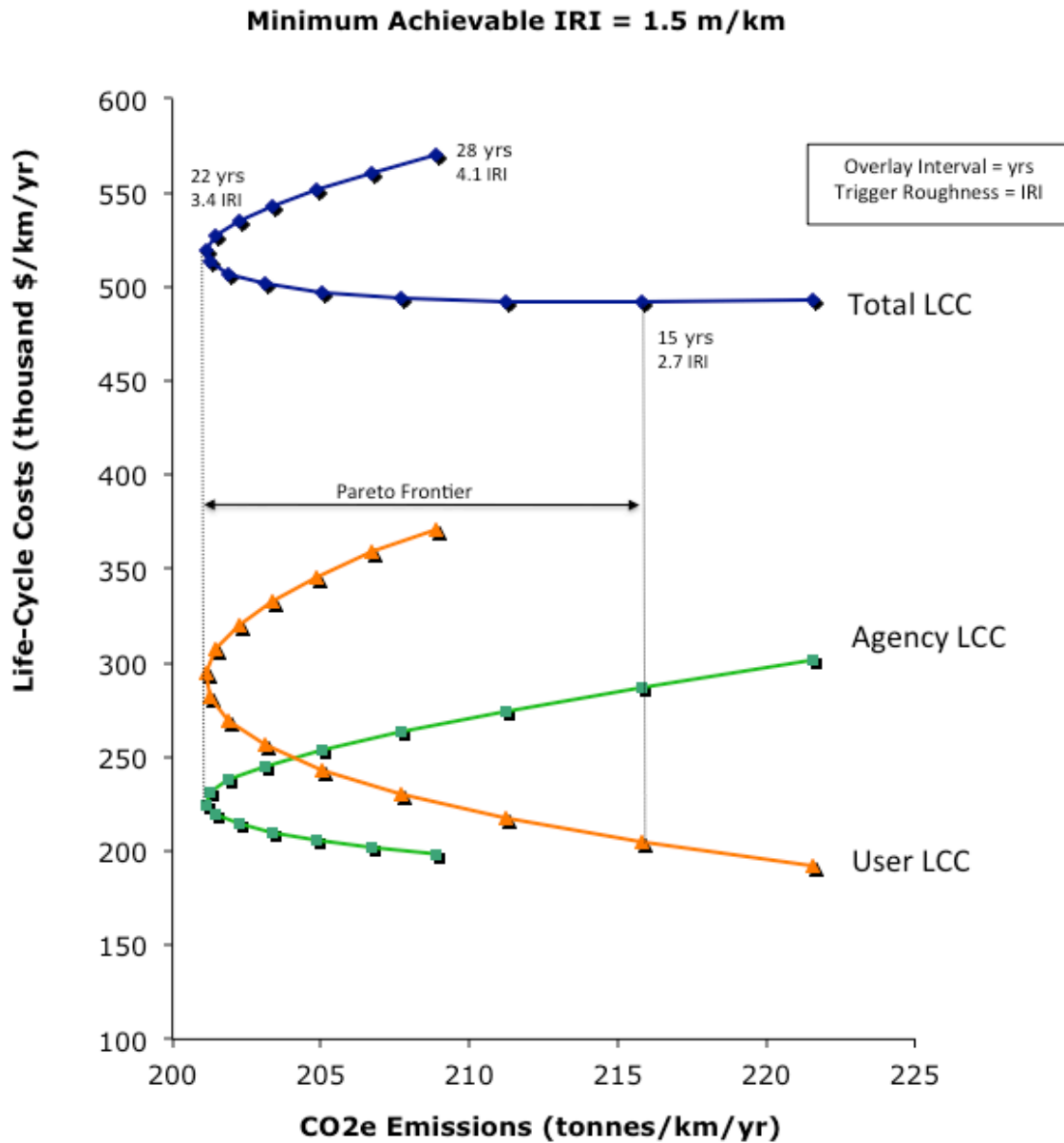
The full set of decision curves provides the additional perspective of the agency only by showing the life-cycle User Costs, Agency Costs, and their sum (Total Costs) plotted against tonnes of CO<sub>2</sub>e emitted for various Overlay Intervals (Figure 9). Note for this particular case that User and Agency Costs trend in opposite directions. Also, User Costs are generally lower than Agency Costs.

Any point along the Pareto frontier subsection of the Total Cost curve is optimal from a societal point of view. However, the decision makers are typically a Department of Transportation, a county, or a city, thus the Agency Cost curve may be of more relevance to them. In this case, it is more desirable to allow the Overlay Interval to increase past 22 years (the emissions optimal) and compare agency dollars per ton of emissions saved in this region.

The figure quantifies how much this emission savings will cost users and ultimately all of society. For example, assume an agency has been applying an overlay to this pavement segment every 15 years. The curve indicates that a change to 18 years will save the agency an additional

\$33,000 (per km/yr), and also save 11 tons of CO<sub>2</sub>e (per km/yr). However, it would also increase User Costs by \$39,000 (per km/yr) and thus cost a societal amount (Total Cost) of \$5,600 (per km/yr). Thus, the agency's marginal cost of such a move is about -\$3,000/tonne CO<sub>2</sub>e, the marginal cost is \$3,600/tonne for the users, and \$500/tonne for society. This tool thus shows decision makers the cost per emission perspective for each stakeholder. By changing the endpoints of the Overlay Interval, both negative and positive costs for saving CO<sub>2</sub>e are possible.

The asphalt overlay thicknesses associated with this case range from 11.2 cm (4.4 in) when applied every 10 years to 13.2 cm (5.2 in) when applied every 25 years. For cost optimal with Overlay Interval of 15 years, the overlay thickness is 11.7 cm (4.6 in), and for the emissions optimal at 22 years, the overlay thickness is 12.7 cm (5.0 in).



**Figure 9: I-80 Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**

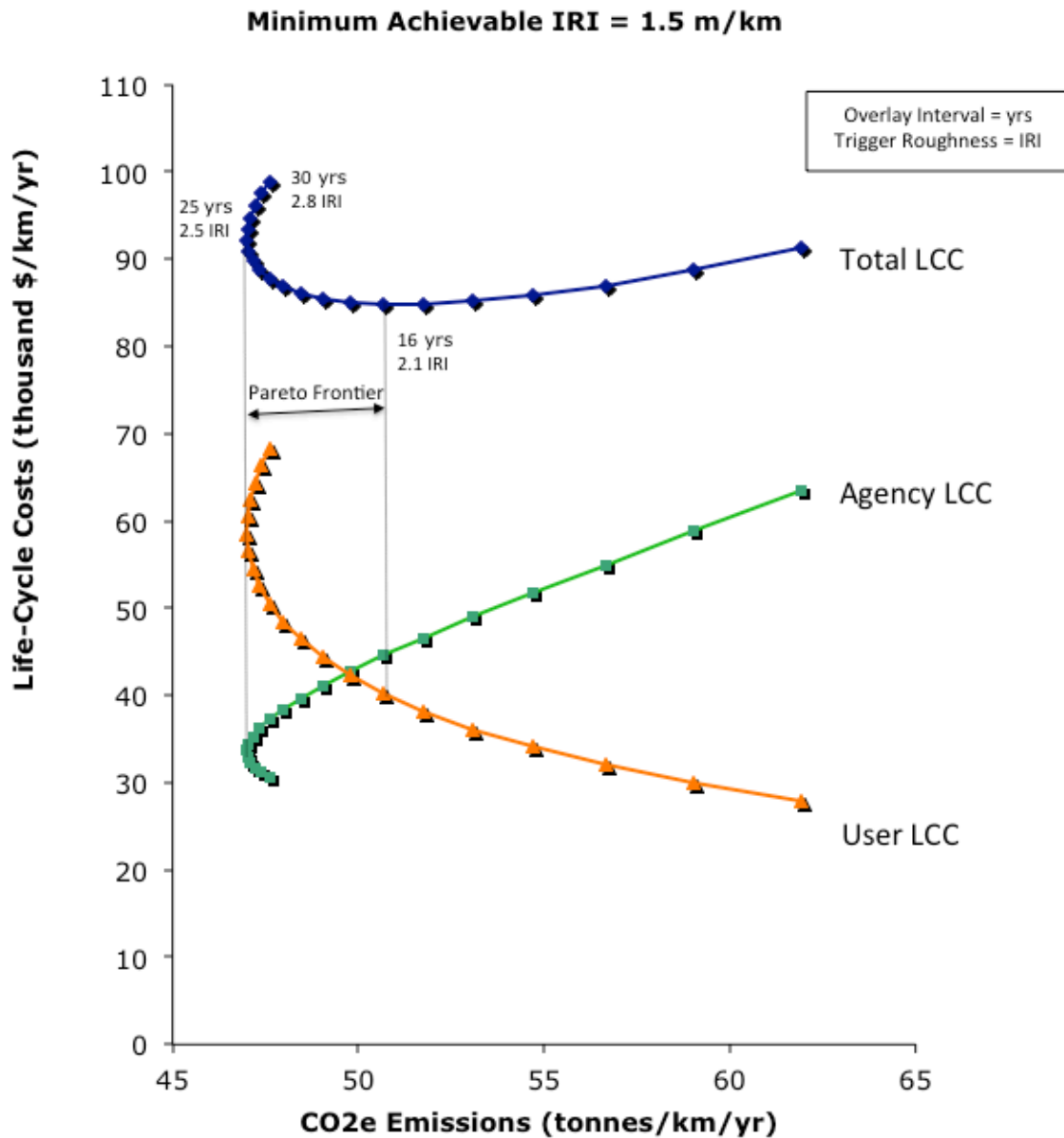
### **4.3 SR-13 Results**

Results for SR-13 appear in Figure 10. In spite of the fact that SR-13 has only two lanes and lower traffic flow, the curve looks very much the same as Figure 9. The main difference is that the magnitudes of the costs and emissions are considerably smaller (about 5 times). The

observation that the Overlay Intervals for both I-80 and SR-13 are approximately equal must be due to the fact that pavements with high traffic volumes are specifically designed to handle higher loads. Nonetheless, the optimization framework is equally applicable to a wide variety of case segments.

The asphalt overlay thicknesses associated with this case range from 10.7 cm (4.2 in) when applied every 10 years to 11.9 cm (4.7 in) when applied every 30 years. For cost optimal with Overlay Interval of 16 years, the overlay thickness is 10.9 cm (4.3 in), and for the emissions optimal at 25 years, the overlay thickness is 11.6 cm (4.6 in).





**Figure 10: SR-13 Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**

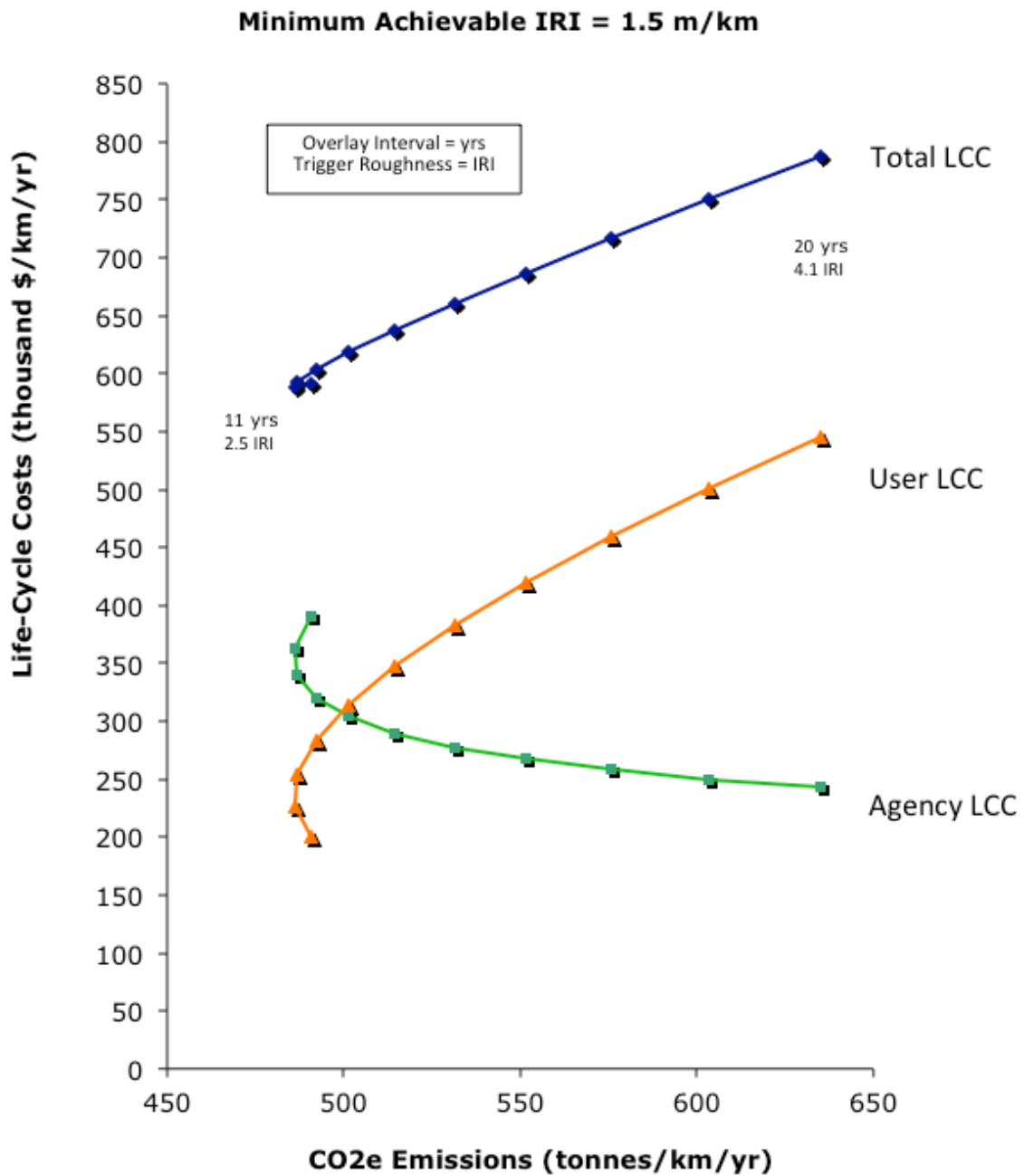
#### **4.4 Sensitivity Analysis**

A sensitivity analysis was performed to evaluate both the possible affects from uncertainty and also potential or actual policy. In this section, several key input parameters for the I-80 case are systematically varied, one at a time, and then compared to the base case

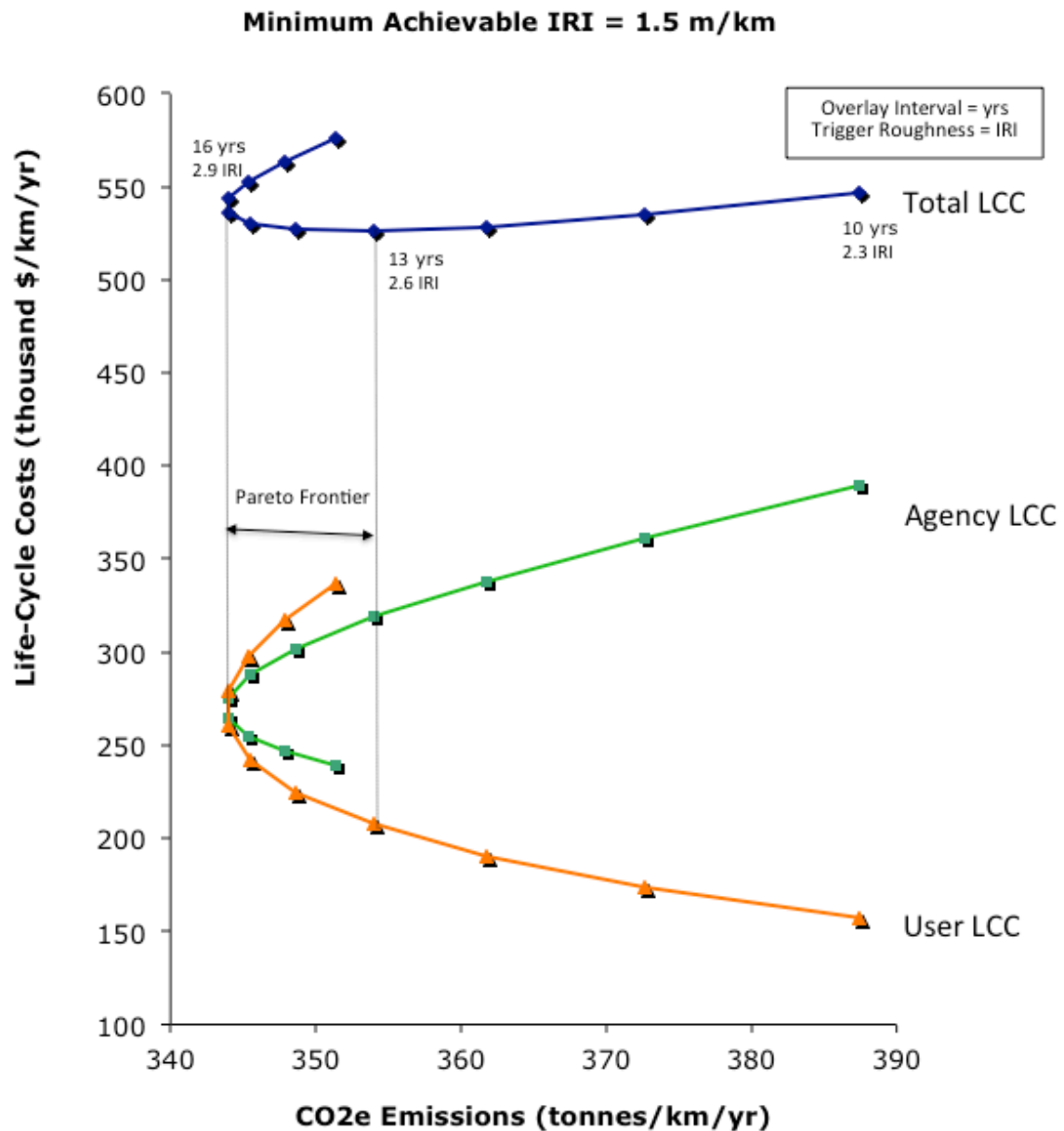
scenario. The “base case” scenario is the case of I-80 with minimum achievable roughness or IRI = 1.5 (m/km). The parameters varied are vehicle miles traveled, minimum achievable roughness, pavement deterioration rate, vehicle fuel economy, pavement supply chain GHG emissions, agency costs, and user costs. Potential correlations to these variations and policies are also indicated.

#### **4.4.1 VMT Growth and Decline**

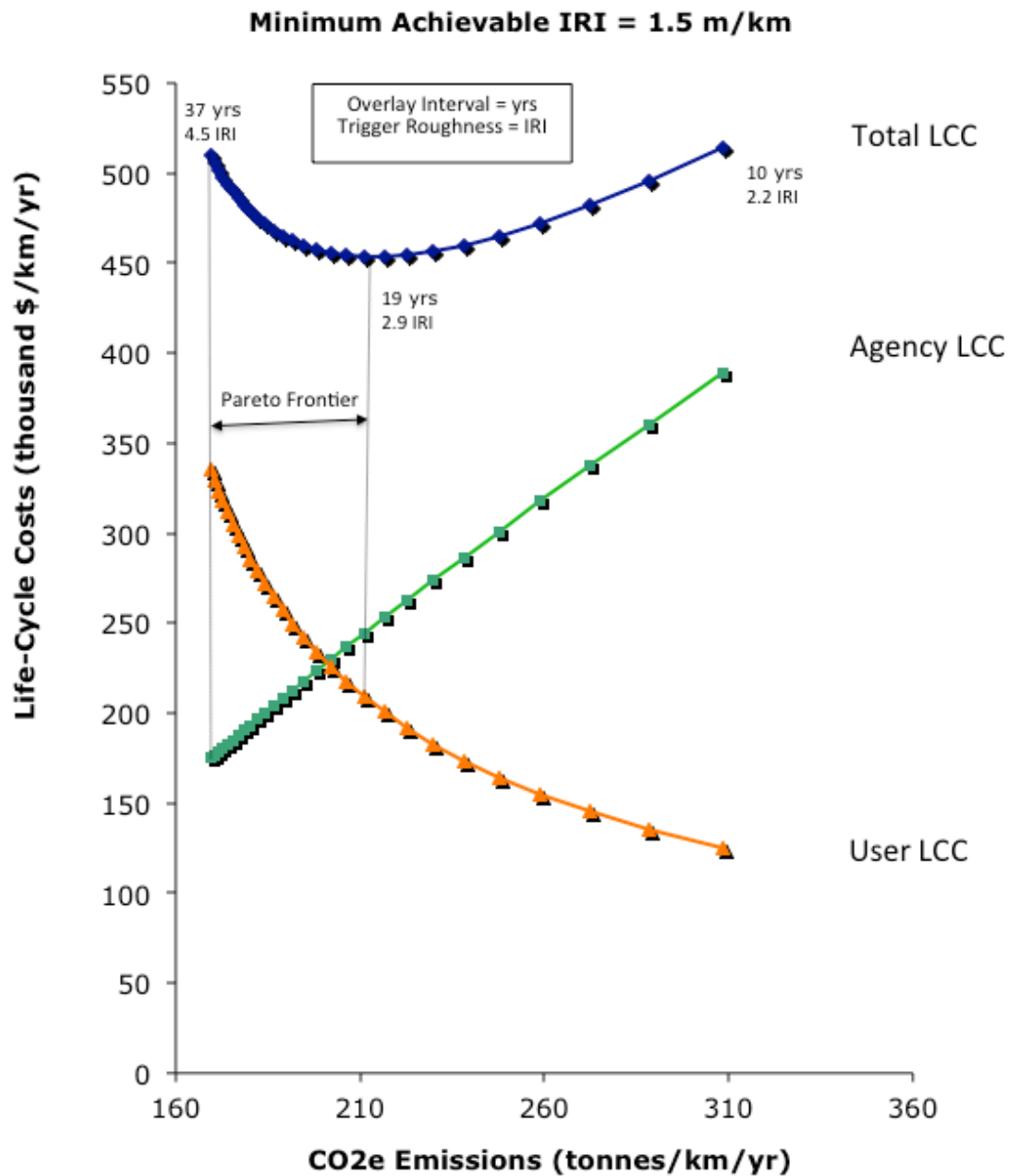
For the base case of I-80, full decision curve results are produced for a VMT increase of 3% annually (Figure 11), 1% annually (Figure 12), and -1% annually (Figure 13). As before, a 4% discount on emissions was required. Notice as the VMT increase goes from 3% to -1%, the Pareto frontier grows in the span of years, and trigger roughness for emissions optimal gets much worse. Thus, this may not be the best strategy for emissions reduction if it entails travelers traversing much rougher roads.



**Figure 11: I-80 VMT Growth 3% Annually - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**



**Figure 12: I-80 VMT Growth 1% Annually - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**



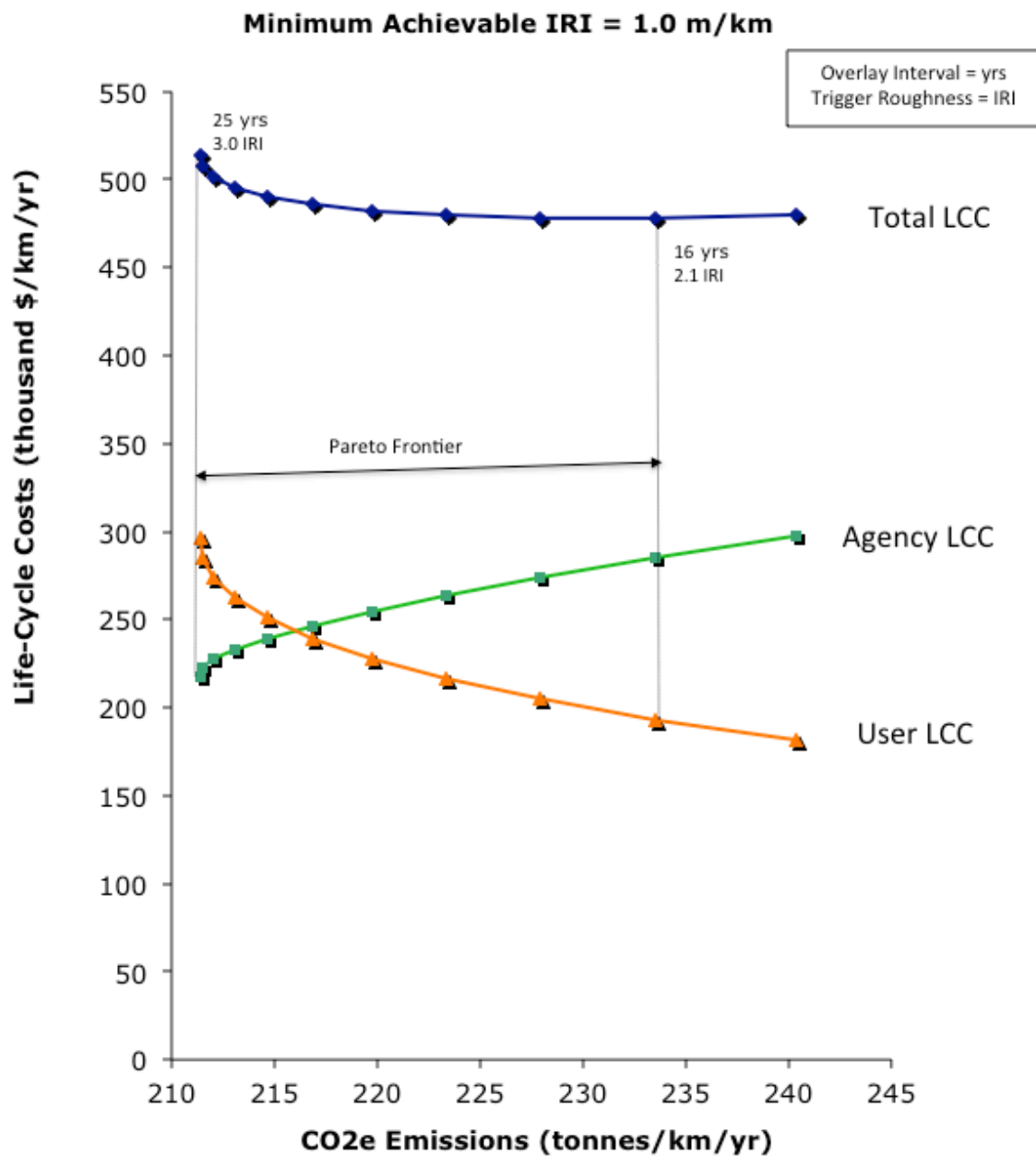
**Figure 13: I-80 VMT Decline 1% Annually - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**

#### 4.4.2 Minimum Achievable Roughness

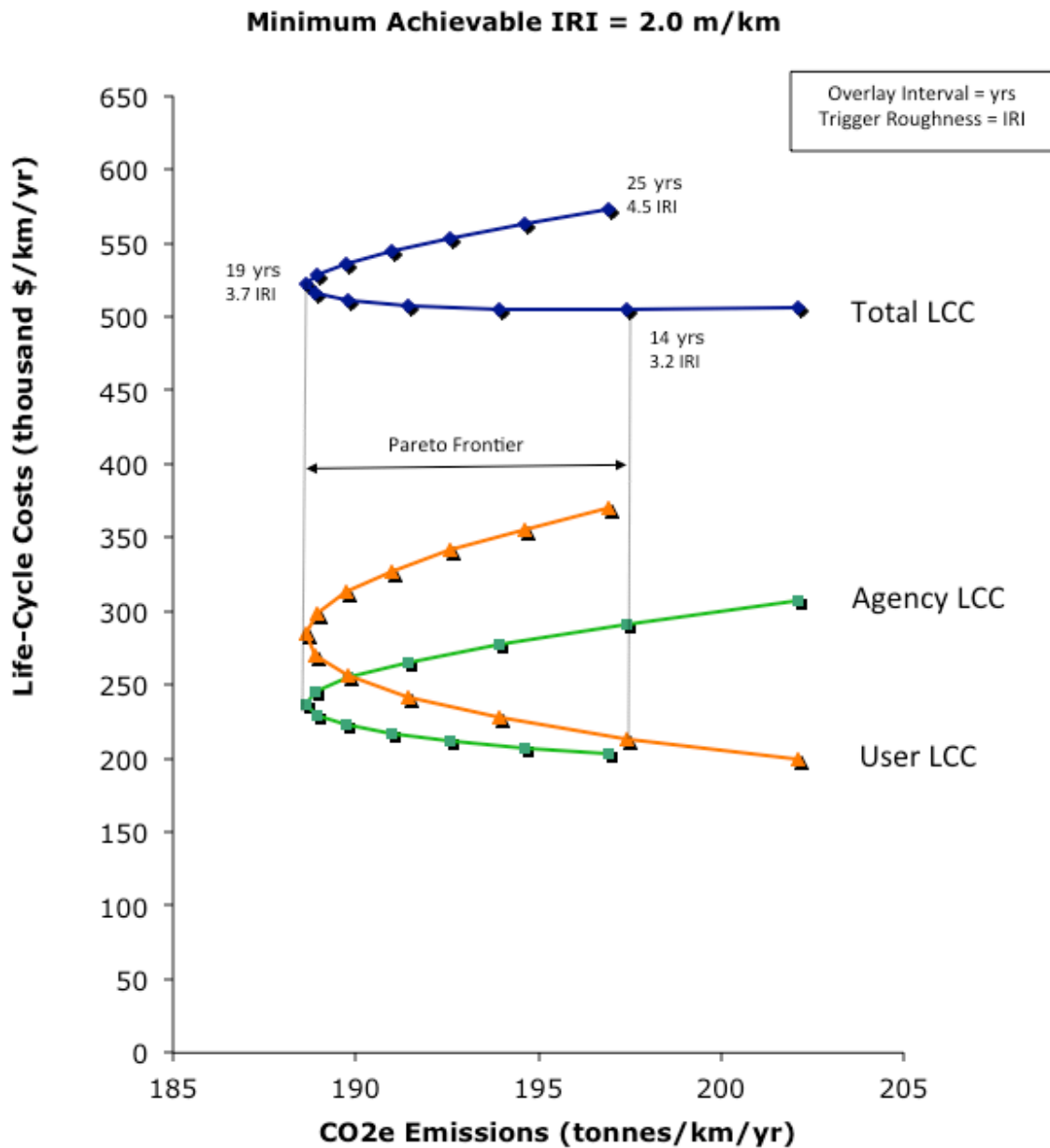
We reconsidered the comparison between Agency Costs and Emissions in Figure 9 for I-80, but for a lower minimum achievable roughness of IRI = 1.0 m/km. From the new results shown in Figure 14, it can be seen that costs fall only slightly (\$14,000/km/yr) and emissions actually increase slightly (10 tonnes CO<sub>2</sub>e /km/yr). This unexpected relation between minimum achievable roughness and Total Emissions is maintained when the minimum achievable roughness is increased (instead of decreased) to an IRI = 2.0 m/km (Figure 15). This is due to the fact that Agency Costs and Emissions dominate User Costs and Emissions.

Further investigation reveals that emissions continue to decrease as the minimum achievable roughness increases until the impractical IRI of 6.5 m/km, at which point the User Emissions becomes a more significant factor. A similar analysis for SR-13 revealed the more intuitive finding that lower minimum achievable roughness saved both life-cycle maintenance costs and Total Emissions as User Emissions easily increase faster with roughness than the emissions associated with applying only two lanes of overlay. A change from a minimum achievable IRI of 2.0 to 1.0 m/km saved approximately \$22,000/km/yr and 27 tonnes CO<sub>2</sub>e/km/yr. Thus, it is tempting to formulate the hypothesis that it matters how many lanes receive an overlay when deciding how rough the rehabilitated pavement should be (or equivalently, how thick the overlay should be).

To test this hypothesis, a scenario analysis is performed where it is assumed that new pavement maintenance policy allows for only the outside lanes (one in each direction) to be overlaid and the other eight lanes to be untouched, as the outside lanes are typically the most damaged from truck traffic. Although the practicality of such a scheme over an infinite time horizon is questionable, the goal is to investigate the mechanism for the unintuitive finding above. Thus the same number of lanes is being rehabilitated in both I-80 and SR-13 locations. For I-80, scenario results indicate that the pavement thickness is more of the driver of this phenomenon than number of lanes paved or Overlay Interval. Even paving only the far outside lanes (one in each direction) does not change the direction of the reverse trend. A change from a minimum achievable roughness of IRI = 1.5 m/km to IRI = 1.0 m/km saved \$10,000/km/yr but cost an additional 4 tonnes CO<sub>2</sub>e/km/yr. Pavement thicknesses increased 2.3cm (0.9 in, approximately 20% increase), which dominated over the relatively small 2-year elongation in Overlay Interval. Thus, the Agency Emissions are large enough to reverse intuition causing the anomaly where rougher roads produce less total emissions. For SR-13, the pavement thicknesses are approximately the same as I-80, but are applied half as often and thus User Emissions are allowed to dominate. This finding implies that traffic loading, pavement thickness, and Overlay Interval all combine to determine when a change in minimum achievable roughness increases or decreases optimal GHG emissions. For life-cycle costs, the lower minimum achievable roughness is always best. This result underscores the fact that optimizing for life-cycle cost does not always optimize for GHG emissions as well.



**Figure 14: I-80 Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.0 (m/km).**



**Figure 15: I-80 Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 2.0 (m/km).**

Results quantify the benefit, for both life-cycle costs and emissions, of a lower minimum achievable roughness. For I-80, each 0.5 IRI (m/km) decrease in minimum achievable roughness is associated with an increase of approximately 11 tonnes CO<sub>2</sub>e/yr/km or decrease in costs of approximately \$13,000/km/yr (Total Costs). For SR-13, the costs also reduced as minimum achievable roughness reduced, but the direction of the relation between minimum achievable



roughness and total emissions is reversed (each 0.5 IRI decrease implies savings of \$11,000 and 13 tonnes CO<sub>2</sub>e saved/yr/km).

### **Policy**

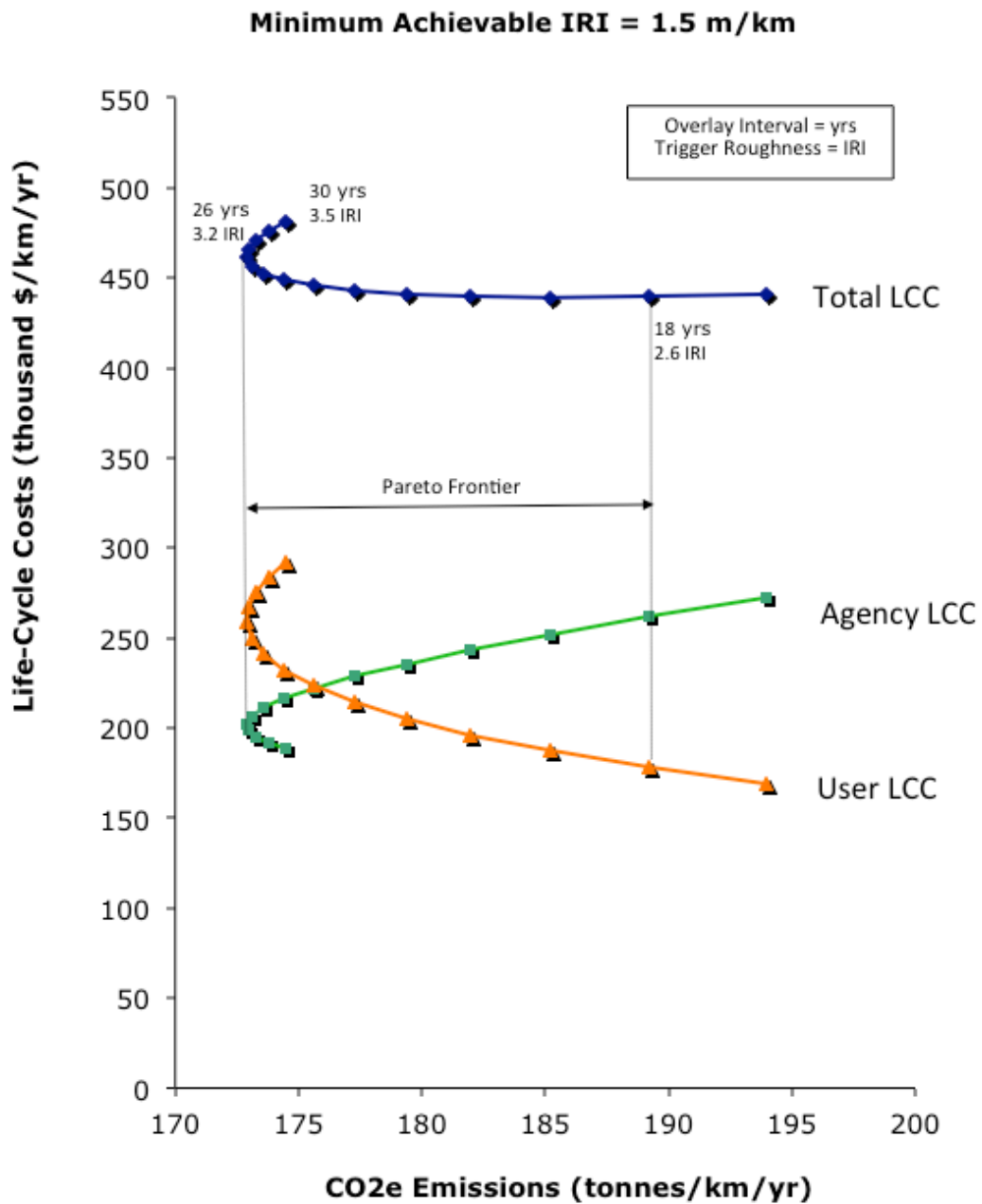
These findings have implications for developing countries where new pavements are still being built. An agency can compare the marginal capital costs for each improvement in pavement minimum achievable roughness to the life-cycle and emission figures above to aid in making decisions about new pavement design levels. For all countries, the decision to improve – and to what extent – a pavement segment with a complete reconstruction can also be aided by understanding the trade-offs, for a particular segment, between emissions and costs.

### **4.4.3 Deterioration Constant**

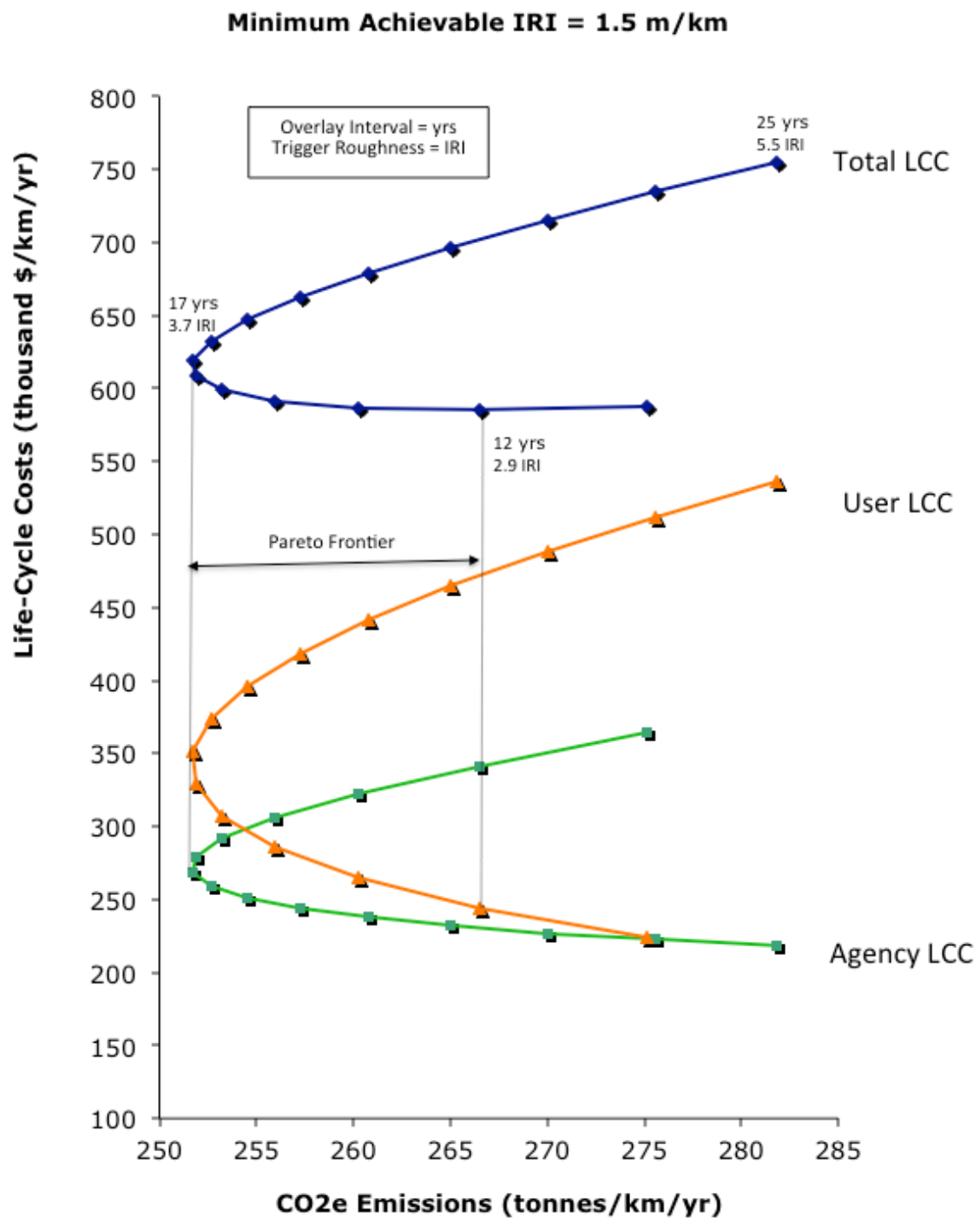
The deterioration constant ( $\beta = 0.0153$ ) is reduced by 50% and then doubled (see Figure 16 and Figure 17). The deterioration constant has an effect on the optimal overlay period as well as the emissions. Roads with a deterioration constant that is half the base case require overlays three years less often than the base case scenario. Minimum emissions dropped by 45 tonnes of CO<sub>2</sub>e/year/km (-14%) and minimum costs dropped by \$85,000 (-11%). The trigger roughness values dropped only a small amount. The faster the road surface deteriorates, the sooner overlays are required driving up costs and emissions. When deterioration rates are doubled, overlays are required 3-5 years earlier, minimum emissions increase 25%, and minimum costs increase 19%. However, the relation between deterioration rate and cost and emission savings is not linear. When deterioration rates were reduced by only 20%, changes in all outcomes were virtually non-existent (Figure 18: I-80 Deterioration Reduced by 20% - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).). Thus, if interpreting the effect of deterioration as uncertainty, the results are robust for this parameter.

### **Policy**

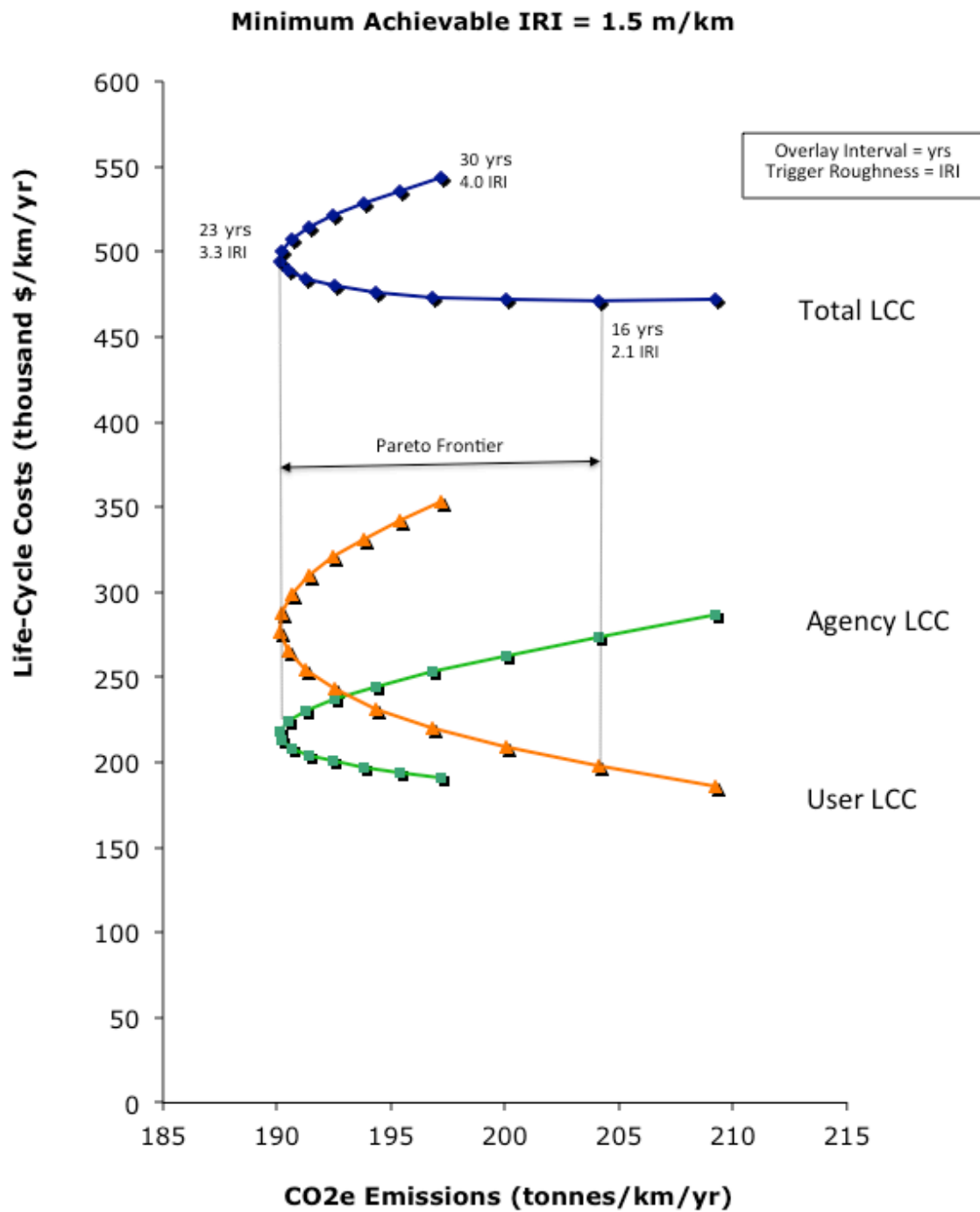
Again, these findings have implications for developing countries where new roads are being constructed at high rates. Efforts to build high quality pavements initially may lead to long-term lower costs and emissions. This is consistent with findings by Madanat et al. (2002), who found that life-cycle costs of roadways are more sensitive to underdesigning than overdesigning. For all countries, pavement durability or overlay durability can be improved with new pavement technologies such as new materials, binders, or aggregates. As it has been shown above, improved pavement durability does not increase trigger roughness as in the improved fuel economy case (below). Emission reducing strategies stemming from durability are superior to fuel economy emission reduction strategies.



**Figure 16: I-80 Deterioration Rate Halved - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**



**Figure 17: I-80 Deterioration Rate Doubled - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**



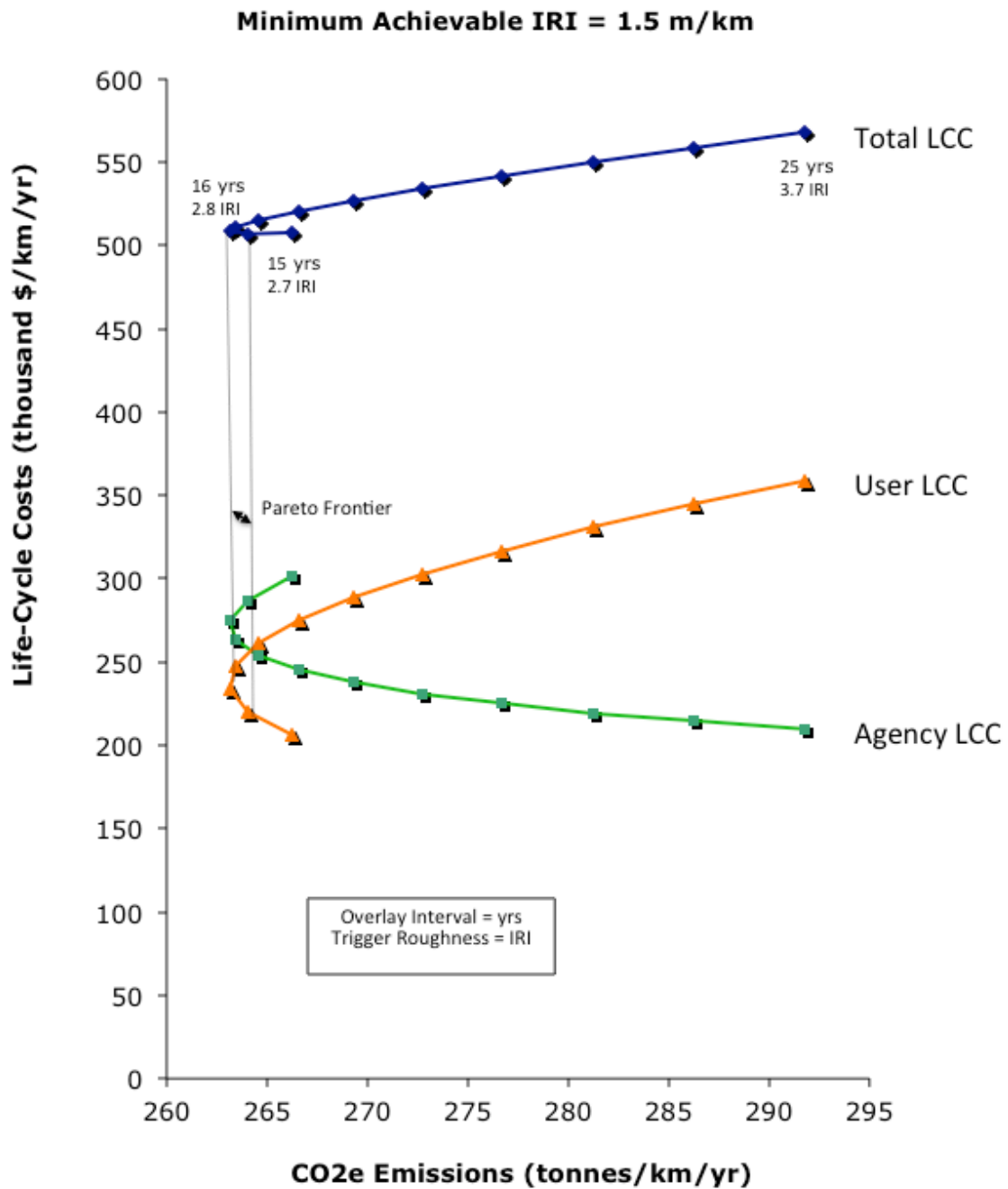
**Figure 18: I-80 Deterioration Reduced by 20% - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**

#### 4.4.4 Vehicle Fuel Economy

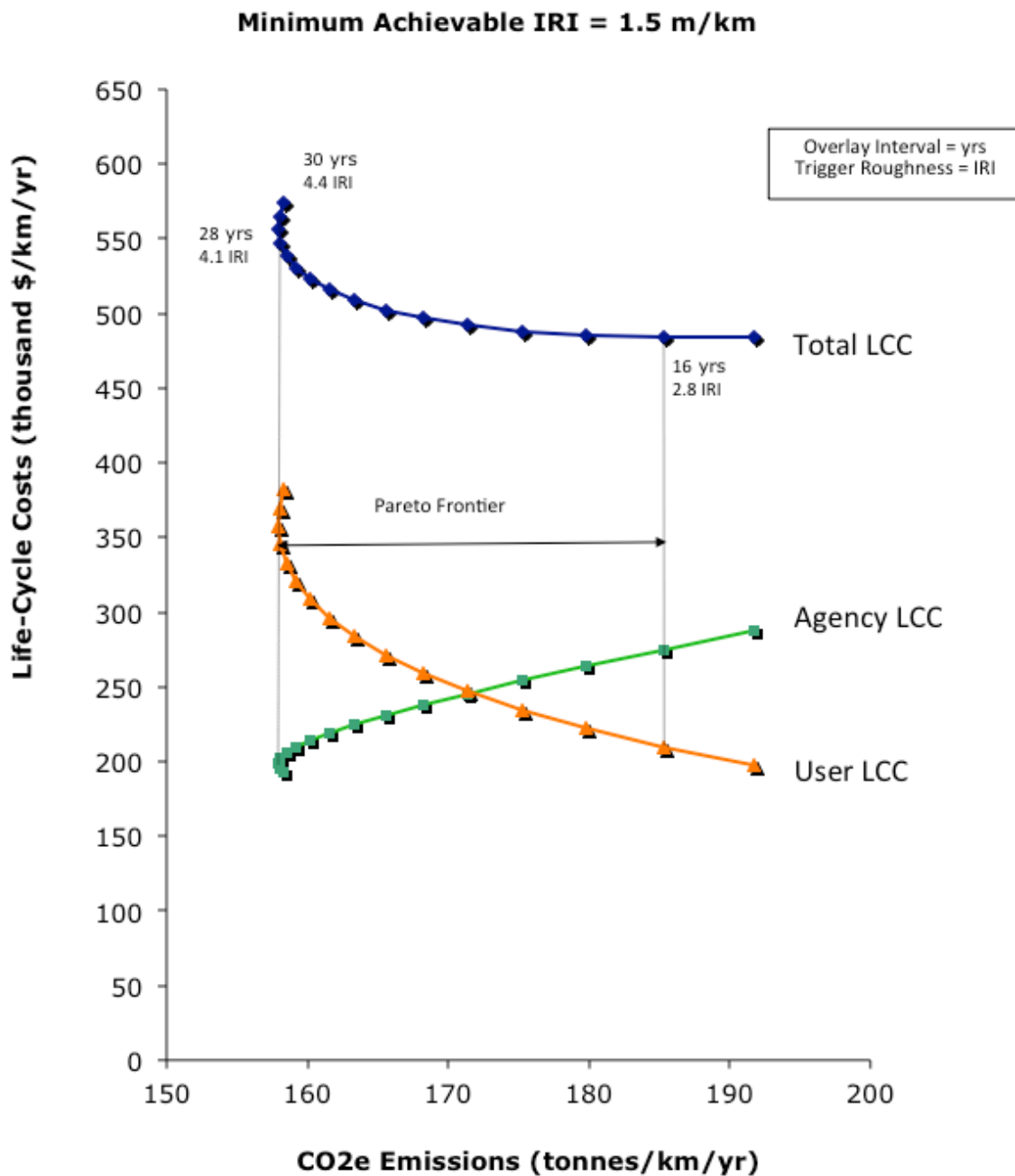
Here fuel economy for both types of vehicles were reduced by half and then doubled. In both cases, we found very small changes in costs but more dramatic changes in emissions and undesirable changes in trigger roughness. When fuel economy is reduced by half (less efficient vehicles), the minimum costs only went up slightly, but the minimum emissions increased 31% (see Figure 19). This is certainly due to optimal Overlay Intervals shortening by 6 years. Also note there is no practical Pareto frontier in this case as the optimal overlay interval for both costs and emissions are separated by only one year (15-16 years). There was only a small effect on Costs for the more fuel-efficient scenario, as overlays are required less often. The more fuel-efficient scenario shows 21% lower emissions and overlays 1-6 years less often (Figure 20). However, with improved fuel economy comes a reduced sensitivity to the pavement roughness and thus the emissions minimum occurs with a trigger roughness above 4.0 IRI meaning roads will become rougher.

##### **Policy**

This sensitivity analysis may inform some policy questions. For example, if heavy trucks in the future were 25% more efficient than today and additionally fueled by natural gas instead of diesel and automobile average fuel economy was to double as per CAFE 2025 standards, they each would produce approximately half the emissions. Thus, instead of applying an overlay every 22 years as in the base-case scenario, the overlay period can be increased to 28 years reducing emissions 21% or approximately 43 tons of CO<sub>2</sub>/yr/km with only a small Total Cost increase (decrease for Agency Costs) but a significant increase in pavement roughness.



**Figure 19: I-80 Fuel Economy Halved - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**



**Figure 20: I-80 Fuel Economy Doubled - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**

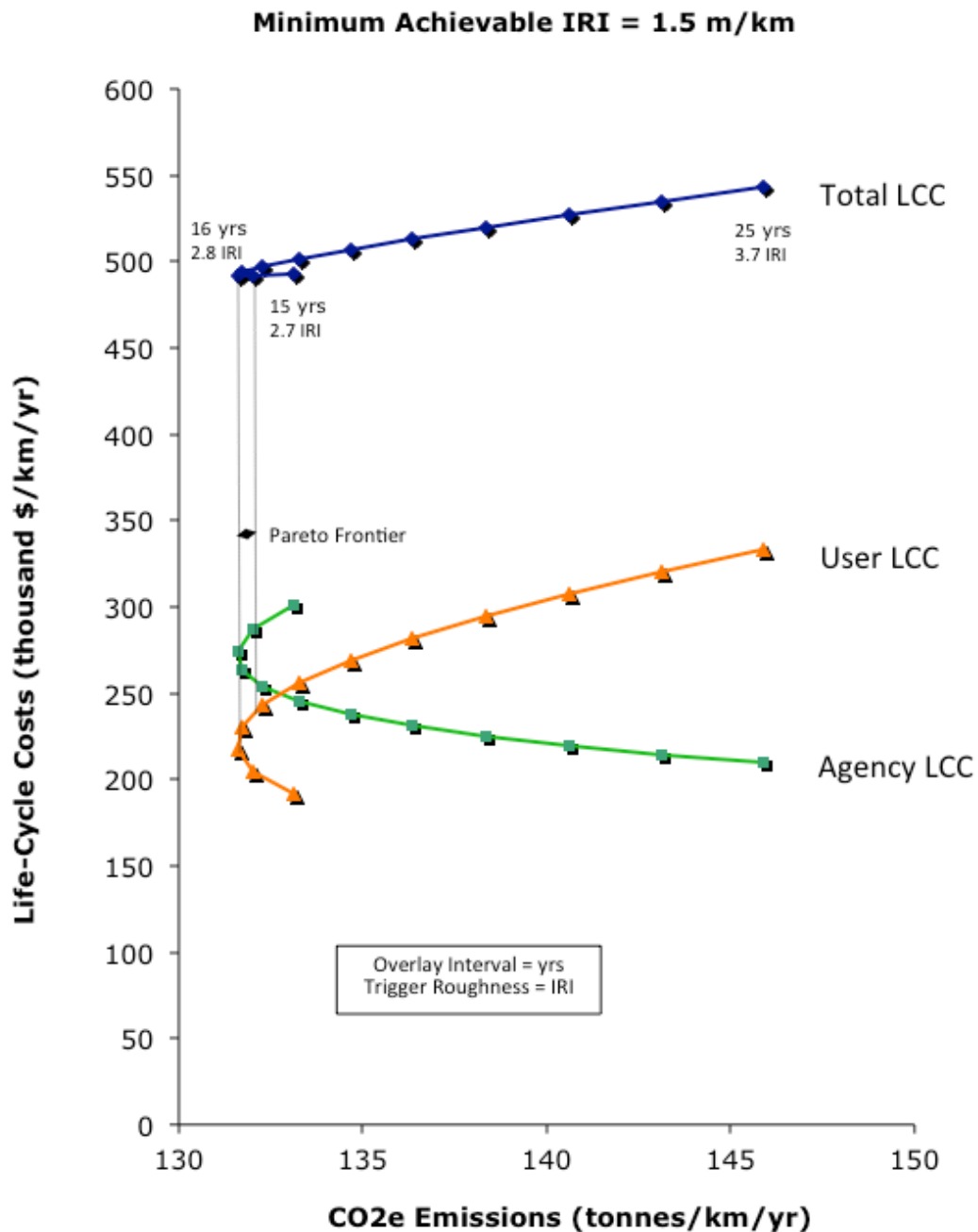
#### **4.4.5 Overlay Emissions**

The estimated values for GHG emissions due to asphalt overlay application used earlier may be too high due to an assumed 10% bitumen mixture (Sathaye et al. 2010). To investigate the sensitivity of the results to overlay technology that may reduce emissions, the overlay emission rate was halved. The results appear in Figure 21 and indicate that the Pareto frontier does not exist as the cost and emission optimal Overlay Intervals are the same. As expected the total amount of GHG emissions decreases approximately 112 tonnes/km/yr (35%). As also expected, User Costs decrease relative to Agency Costs as the Overlay Intervals are shorter and trigger roughness decreases by 0.6 IRI or 18%. Total Costs remain relatively constant. Thus, results for this study are very sensitive to the overlay supply chain emissions. Overlay technologies that reduce emissions for overlay application significantly will substantially reduce total emissions and trigger roughness.

##### **Policy**

This scenario corresponds to improved overlay technology such as in-place recycling or single-lane rehabilitation instead of all lanes. Although costs are likely to also be reduced by these and other technologies that reduce emissions for overlay application, this analysis does not take into account cost reductions. The finding that reduced overlay emissions will save a lot of Total Emissions and also provide smoother pavements makes this method of emissions reductions superior to vehicle fleet fuel economy improvements. However, since we can anticipate future fuel economy improvements due to either increased energy costs, government regulation (CAFE), or both the need for increased research in overlay technology is a priority in order to balance out the roughening effects of the improved fuel economies.



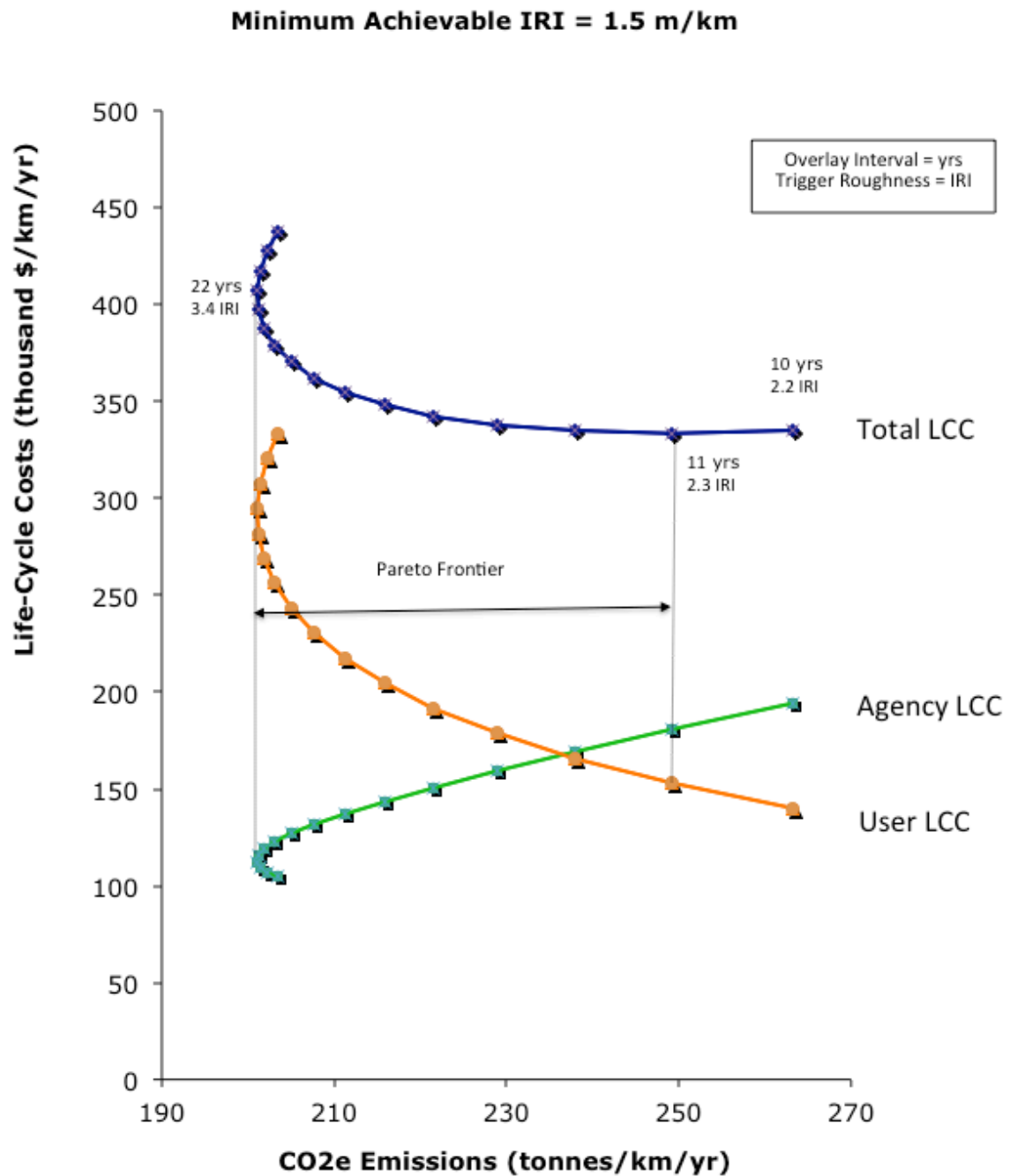


**Figure 21: I-80 Overlay Emissions Halved - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**

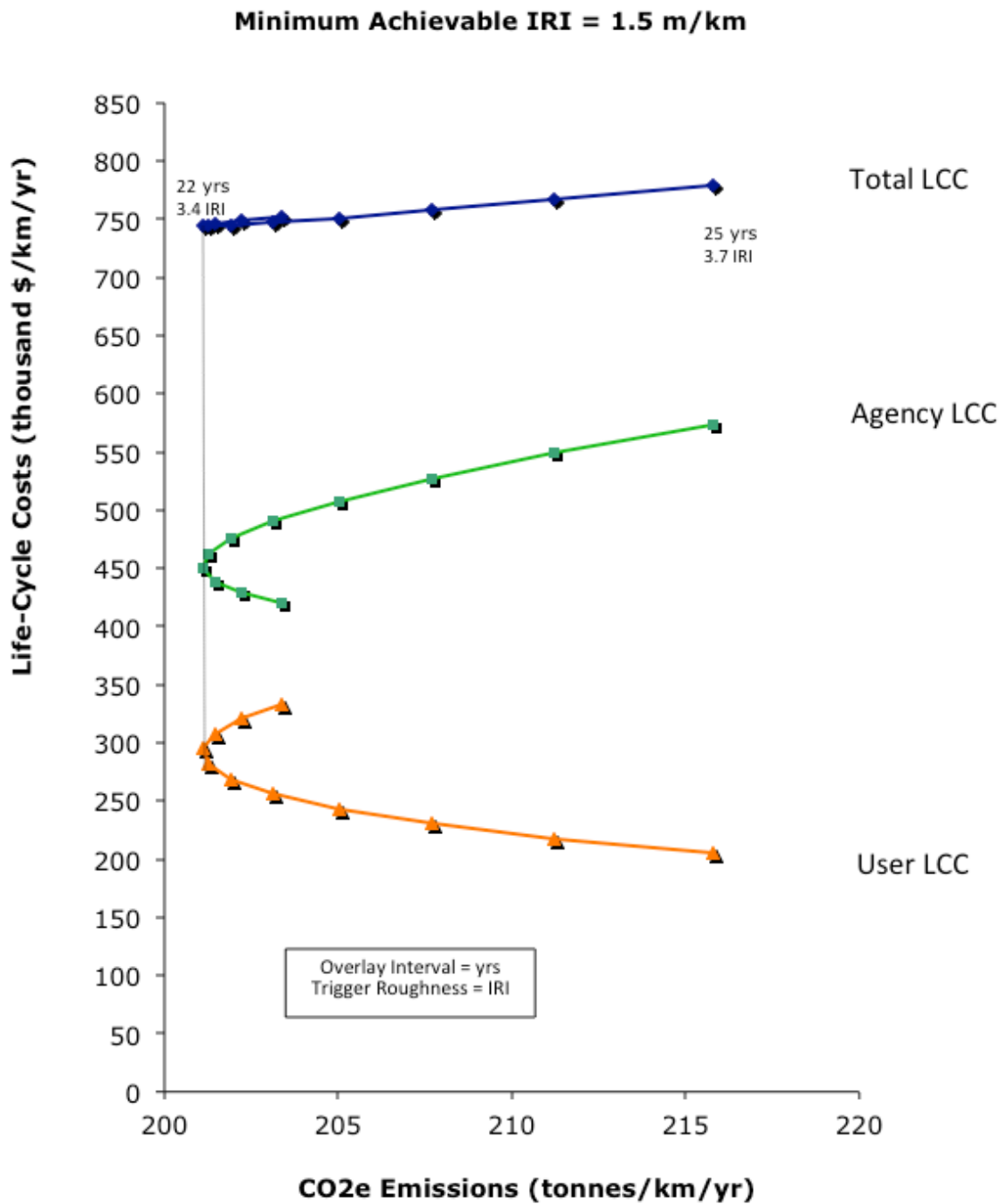
#### 4.4.6 Agency Costs

Agency Costs were cut in half and then doubled. The results appear in Figure 22 and Figure 23. As expected when costs assumptions are reduced without changing emission

assumptions, the emission optimal stays the same, while the costs change dramatically. Cutting Agency Costs in half allowed for much more frequent overlays, which lowers the trigger roughness for the cost optimal. Doubling the Agency Costs raises the Total Costs and also brings the two optimal overlay intervals to within one year of each other making the cost optimal have a much higher trigger roughness. To better reflect new overlay technology improvements, it may be better to combine the overlay emission sensitivity analysis with Agency Cost sensitivity analysis.



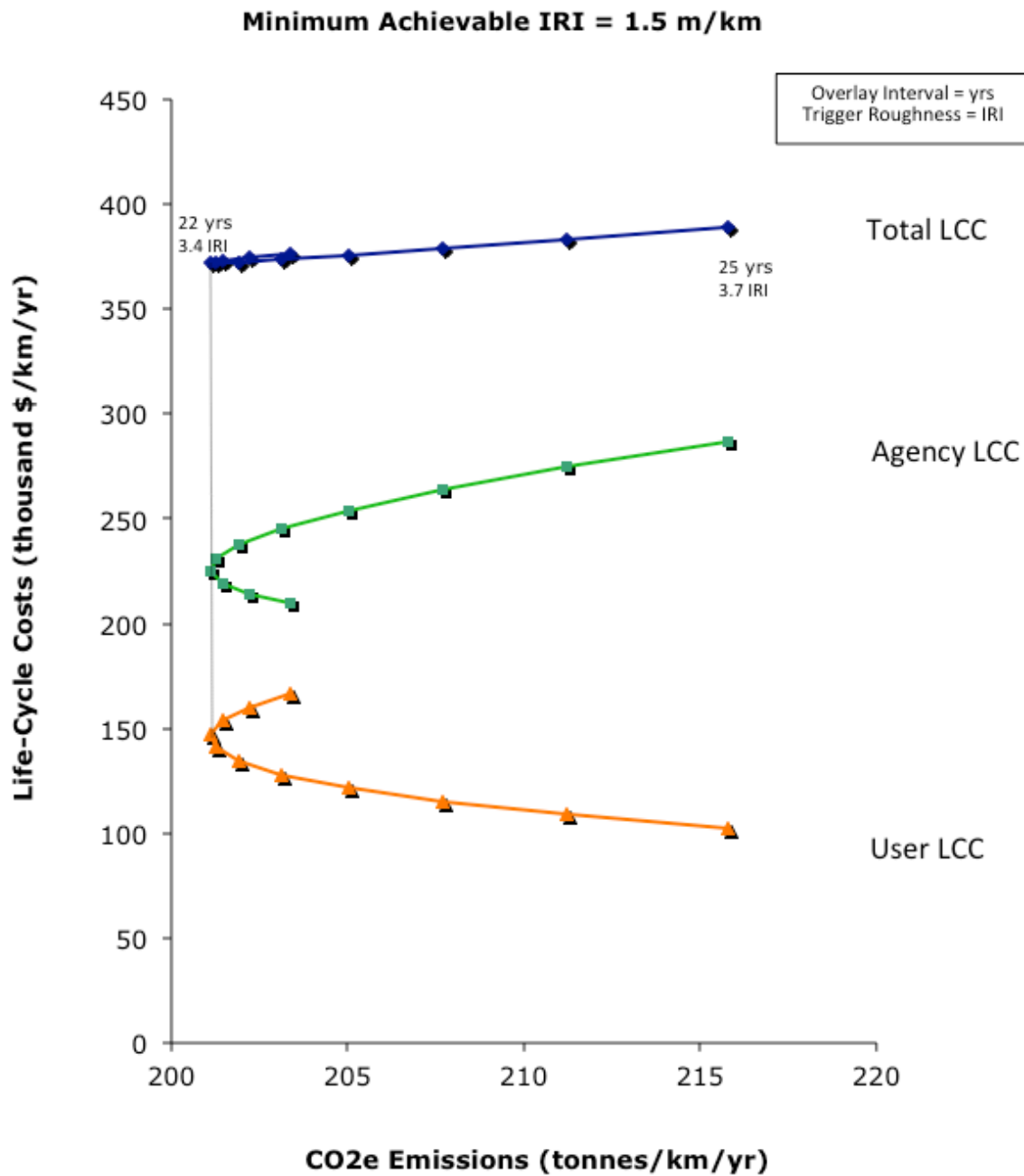
**Figure 22: I-80 Agency Costs Halved - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**



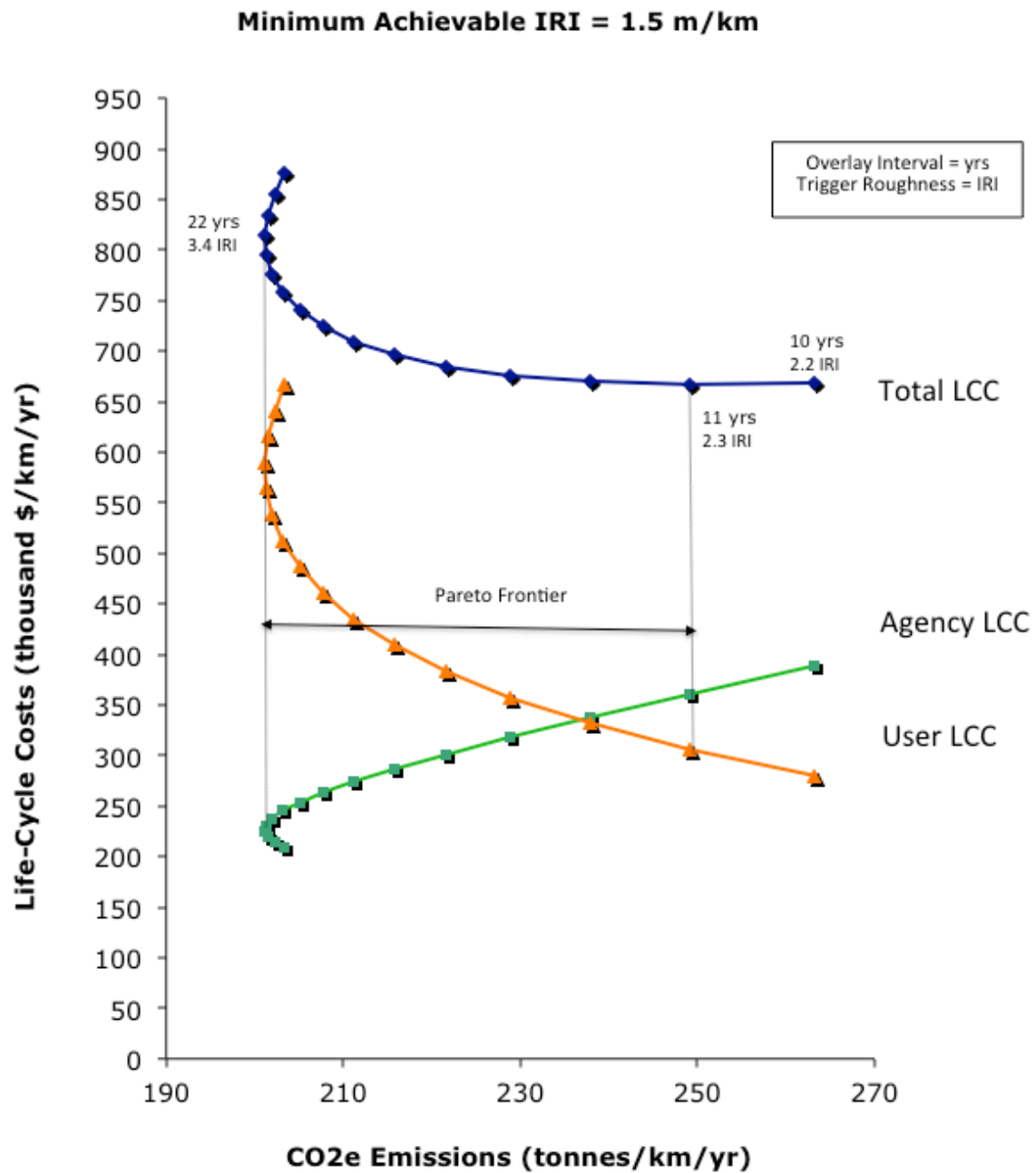
**Figure 23: I-80 Agency Costs Doubled - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**

#### **4.4.7 User Costs**

The User Costs were halved and then doubled. The resulting decision curves appear in Figure 24 and Figure 25. Interestingly, the plots look almost exactly the same as the Agency Cost results but with axes flipped between the two different sensitivity analyses. This suggests that doubling the Agency Costs has the same effect on the system as halving the User Costs and vice versa.



**Figure 24: I-80 User Costs Halved - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**



**Figure 25: I-80 User Costs Doubled - Decision Curves for Total, Agency, and User Life-cycle Costs by CO<sub>2</sub> Emissions for One Kilometer of Highway at Minimum Achievable IRI = 1.5 (m/km).**

## 4.5 Policy Analysis of Emission-Reducing Strategies

To illustrate how the sensitivity analysis can be used to analyze policy, two emission reducing strategies are considered and the changes to Total Cost and Emissions outcomes are determined. The first example is based on fuel economy. In 2010, the EPA announced, for the first time ever, fuel economy and GHG emission standards for heavy-duty trucks that are to take effect in 2018 (New York Times 2010). Then in 2011, the National Highway Traffic Safety Administration enacted new CAFE standards for light-duty vehicles for each year up to 2025 (EPA 2011). Results for combining both of these new legislations for the year 2018 are presented in this section. The second example is for the situation where land-use planning, parking pricing, road pricing, gas taxes, or other climate change policies cause a reduction in VMT of 1% annually. Results for this scenario are presented in the next section.

Sensitivity to emission-reducing policy results are given in the form of four parameters. There is both a change in Total Cost and Total Emissions from each of the Total Cost minimum and the Total Emissions minimum. The parameters can be visualized by the dashed horizontal and vertical components of the red vectors in Figure 26.

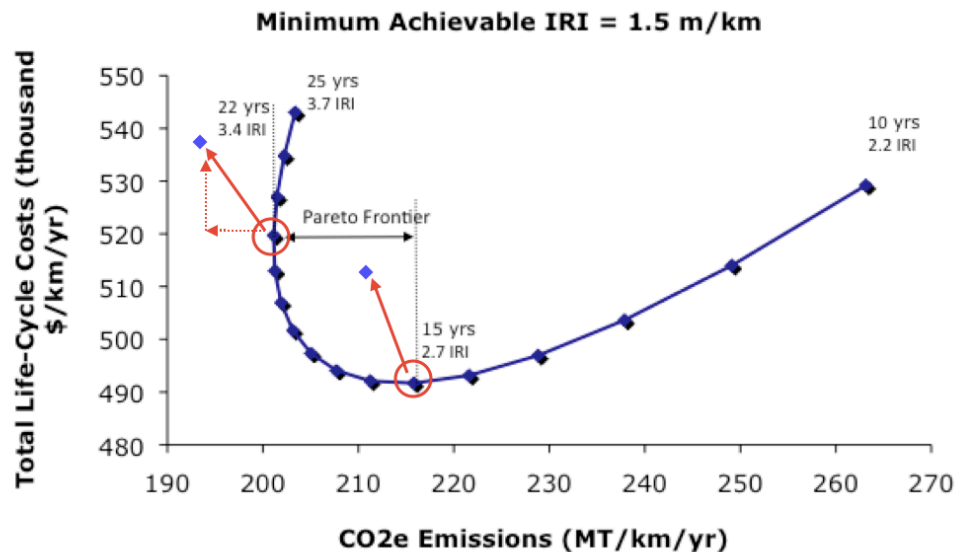


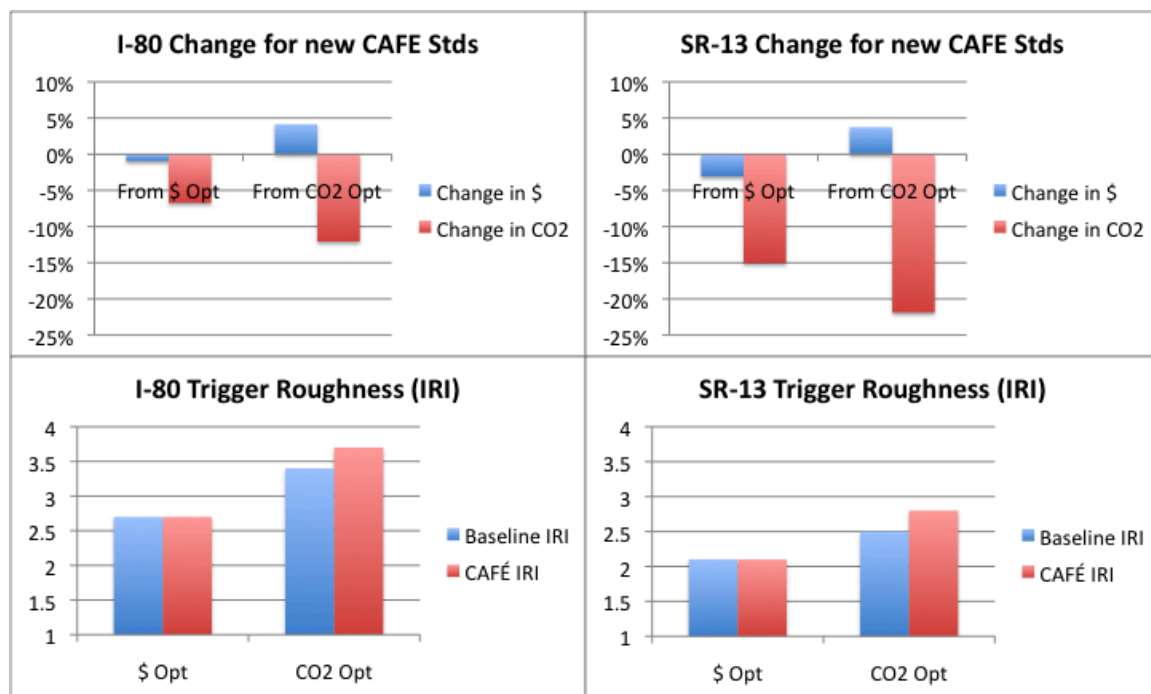
Figure 26: Illustration of Optimal Value Shifts from Sensitivity Analyses

### 4.5.1 CAFE and Heavy Truck Standards in 2018

The new EPA fuel economy and emission standards for heavy-duty trucks were combined with the new CAFE standards for 2018. As estimation of fleet fuel economy averages for this year are beyond the scope of this study, it was assumed that at some point the heavy-duty and light-duty vehicles average the standards. The results indicate for the I-80 case a small cost savings at the cost optimal but a cost increase at the emissions optimal (Figure 27). This is certainly due to the new trigger roughness for emissions optimal being so far away from that of the cost optimal. Emissions are reduced at both optimals but more so at the emissions optimal (as expected). For the arterial case of SR-13, we see a more dramatic relative improvement, but undoubtedly the magnitude of the cost and emissions savings is less than in the larger highway



case. Note that for both cases, the emissions optimal occurs at a higher trigger roughness than before, thus the pavements will be rougher for travelers.

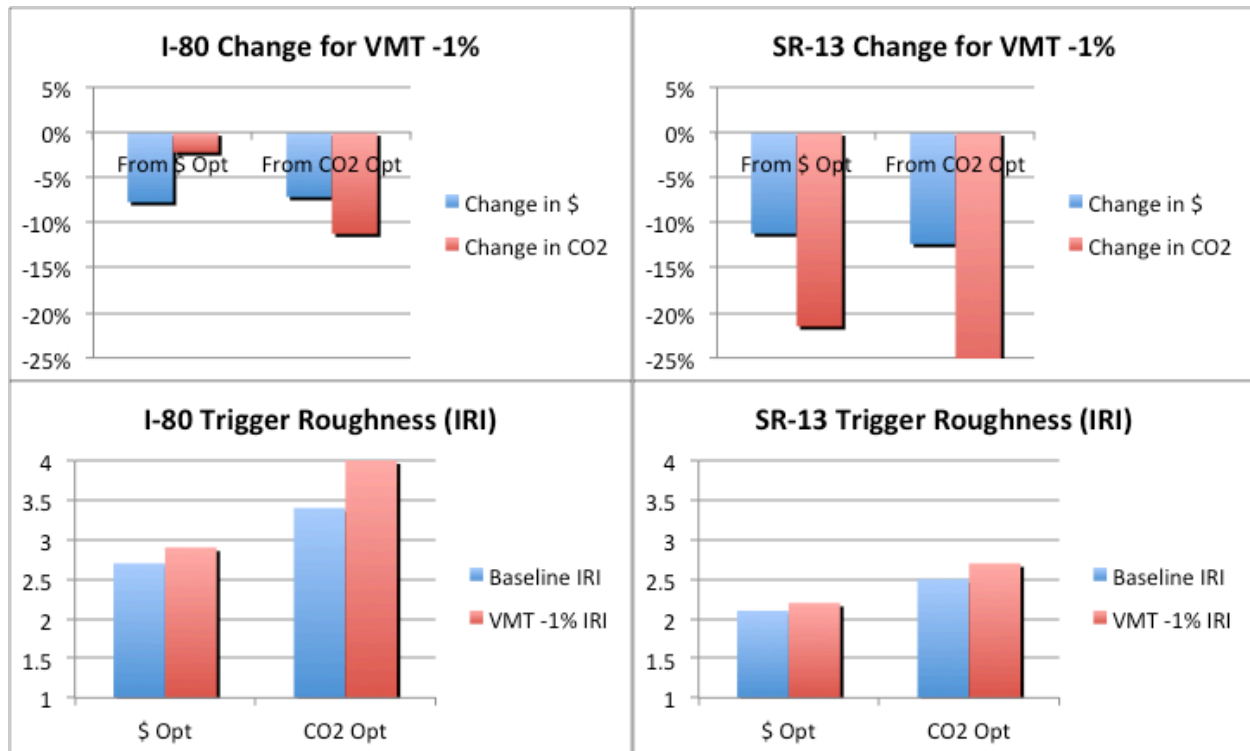


**Figure 27: Results for CAFE and Heavy-duty Truck Standards for 2018.**

## 4.5.2 VMT Reduction Policy

As a result of some form of demand management policy intervention, this scenario assumes that VMT reduces by 1% annually. In most cases this means that there is no emissions optimal as Overlay Intervals continue to increase, Total Emissions continues to reduce. This is certainly from the number of vehicles dropping each year and the pavement deterioration rate subsequently reducing as a result of the reduction in traffic loading. Thus, the emissions from vehicles that would ordinarily increase due to the increased roughness from higher Overlay Intervals just did not happen. Therefore, a maximum Overlay Interval of 30 years was used as an analytical endpoint. As another caveat, in order to avoid violation of the steady state assumption of our models, a discount rate for emissions of 4% was introduced just for this one scenario. The rate of 4% was used simply because this is the value Caltrans uses for costs (Caltrans 2007b), and there is little consensus on emissions discounting, let alone the discount rate (Cline 2004, Guo et al. 2006, and Hepburn 2006).

The results indicate superiority over the fuel economy emissions reduction strategy as costs do not increase at either optimal (Figure 28). Note that trigger roughness is worse at both cost and emission optimals for this policy. Emission reduction policies that don't force travelers to use rougher roads are considered in subsequent sensitivity analyses.



**Figure 28: Results for VMT reduction of 1% per Year.**

## 4.6 Case Studies Findings

*Research Objectives:* The original goals of the case studies were realized. The practicality of the developed analytical framework has been established and the process is simple enough for use by decision makers. Detailed estimates of total life-cycle costs and total GHG emissions were gained with perspectives for both agencies and users. The Pareto frontiers were identified and couched within the larger decision curves that are products of the optimization process and tools designed for use by decision makers. Cost-effectiveness estimates for proposed or actual changes in pavement management policy are easily determined from the decision curves. The sensitivity analysis identified how each input parameter varied affects the key outcomes such as Overlay Interval, trigger roughness, and total life-cycle costs and GHG emissions. Two emission-reducing policies were successfully analyzed for their effects on pavement management optimization with both expected and unexpected results.

*Case Study Generalizability:* The California case studies selected revealed findings for two types of roadways: one a large ten-lane highway that supports commuter traffic in and out of a major city downtown region, and the other a more typical two lane surface street within a city. Other types of roadways such as four-lane interstate-highways or four-lane arterial roads exist somewhere in between these two case studies.

To the extent that the case pavement segments represent other highway segments in California or elsewhere in the United States is a function of aligning the pavement deterioration rates, the traffic loadings, and the number of lanes. A two-lane highway in downtown Los Angeles may have been constructed to a higher structural number (quality) or a two-lane highway in the Lake Tahoe area may deteriorate more quickly due to the annual freeze-thaw

cycles. As traffic delay due to pavement rehabilitation activity is not accounted for in the costs or emissions estimates, the results of the case study only apply for major metropolitan areas within California or other regions where these activities are specifically performed only at night. However, the pavement improvement function, and the agency and user cost estimates along with the agency and user emission estimates are not particular to California and can be applied to pavement segments for all of the United States. Thus, these case study results are generalizable to other roadways in California or the United States as long as adjustments are made for the pavement deterioration rates, the traffic loadings, the number of lanes, and traffic delays due to rehabilitation activities. The results of the sensitivity analysis should help in making the adjustments.

*Sources of Uncertainty:* Uncertainty enters into the case study results at every instance. Simplifying assumptions for the theoretical model such as a pavement deterioration function that only requires parameter inputs that are available easily, a pavement improvement function based on empirical data from out of state, and an optimization framework that makes use of an infinite time horizon and steady state conditions all contribute to errors. Model parameter inputs are often estimates, not measured data. Agency cost estimates were required to be a function of overlay thickness as per model assumptions and thus were adjusted to 2011 dollars from many years prior. User cost estimates were required to be a function of pavement roughness and also had to be adjusted to 2011 dollars but were more current. As is typical of LCA studies, the GHG emission estimates for the asphalt overlay are potentially inaccurate. The user emissions are more accurate as the average fuel consumption is relatively well known and documented as is the total amount of CO<sub>2</sub> associated with each gallon of fuel. However, only one point estimate was used for heavy-duty truck fuel economy although there are several types, sizes, and load factors for this category of trucks. Also, wear and tear due to pavement roughness was accounted for in the user cost estimates, but not the emission estimates. The additional costs and emissions due to traffic delays caused by lane closures required for pavement rehabilitation activity are also not accounted for as these activities are performed at night by Caltrans in the major metropolitan regions.

*Data Quality Assessment:* Since the results of a study such as this are dependent on the quality of the data, an assessment of the data quality is important. Interpretation of the results is subject to qualifying the credibility and robustness of the data. Higher data quality provides more confidence in the results and makes more defensible any decisions based on them.

A data quality assessment is summarized in

Table 2. The data quality values used are based on the scale utilized in Junnila et al. (2006). Table column headings correspond to the following goals: data should be calculated based on measurements, information should be verified, data should be representative even if from a smaller number of sources but for adequate periods, data should be less than five years old, specific local data should be used, and data should be representative of the technologies associated with the processes and materials under study.

The pavement load parameters (ESALs - *I*) were estimated by Sathaye et al. (2010) and represent refined estimates from Caltrans. However, the Caltrans estimates are unreliable as they do not have a documented source year. Similarly, the pavement construction quality parameters (Structural Number - *N*) are also estimated by Sathaye et al. (2010) by using assumptions from the California Highway Design Manual (Caltrans 2009). Although the Sathaye et al. (2010) data sources are from several years prior, the pavement parameters utilized are not changing quickly and represent the best information available. The pavement improvement parameters are estimated from empirical work by Tsunokawa and Schofer (1994), but are out of date and may not reflect current practices. Traffic volumes are estimated by Caltrans and are known to be gathered from electronic sensors so that they have some validity. However, even these estimates are not associated with a documented source year. Vehicle fuel economy is accurate if California is represented by the United States. The estimates were gained from the Federal Bureau of Transportation Statistics (2006) and Barnes and Langworthy (2004). In spite of the sources being somewhat out of date, evidence shows fleet fuel economy to be flat since that time period (Bureau of Transportation Statistics 2006). This is partly due to new vehicles being only a small percentage of the vehicle fleet with heavy-duty trucks having even a lower turnover rate than light-duty vehicles. User emissions were estimated from the fuel economy of the vehicles and adjusted to account for the best-known estimates of supply chain emissions. These emissions are among the best known of emissions estimates except for the fact that they are a function of the fuel economy estimates. Also missing are emissions associated with vehicle wear and tear (assumed to be relatively small as compared to tailpipe emissions). The agency emissions estimates are from Sathaye et al. (2010) and represent the worst of the input parameter estimates. Pavement supply chain emissions are a function of many characteristics, such as roadway location, where bitumen is processed, and how far aggregate is transported. However, the largest portion of the emissions is due to the bitumen production from petroleum. As this process, based on hot-mix asphalt, has not changed in recent years, the results still apply regardless of location variations. User costs for non-fuel related items have been estimated several years ago (Barnes and Langworthy 2004) and their relative magnitudes have most likely not changed significantly. They have been adjusted to 2011 dollars in the current study. The fuel-related costs are based on actual 2011 gas price averages for California (Energy Information Administration 2011) and are very accurate. However, the total user cost component due to fuel is still contingent on the fuel economy estimates. Agency costs are estimated from an old study (Small et al. 1989) but represent the only reliable source of agency costs as a function of pavement overlay thickness and were adjusted to 2011 dollars. Thus, the poor data quality score for these input parameters.

**Table 2: Case Study Data Quality Assessment**

Input Parameter	Acquisition Method	Independence Of Data Supplier	Representativeness	Data Age	Geographical Correlation	Technological Correlation
Pavement Loads	2	3	1	3	1	1
Pavement Construction Quality	3	2	2	3	1	2
Pavement Improvement	1	2	3	3	3	2
Traffic Volumes	2	3	1	3	1	1
Vehicle Fuel Economy	2	1	2	2	2	2
User Emissions	1	1	2	2	2	2
Agency Emissions	3	2	2	2	2	3
User Costs	2	2	3	3	2	2
Agency Costs	2	2	3	4	2	2

Maximum quality = 1, minimum quality = 5

*Significant Digit Analysis:* It is important to have a practical notion for the magnitude of a discernible difference between two cost or emissions values. It doesn't make any sense to say that one scenario reduces costs over another when the difference is a few dollars. Statements about differences have to be made relative to a meaningful unit of difference. Thus, in spite of the fact that many results are presented in this study with small changes or differences, reported changes or comparisons are not meaningful in increments smaller than this unit of difference. To this end, a simple significant digit analysis follows.

Agency life-cycle costs and GHG emissions are a function of the asphalt overlay thickness. Asphalt overlay applications can be as accurate as approximately one centimeter in thickness, thus we have a meaningful unit of difference for the agency. Assuming a worst-case scenario of a minimum Overlay Period of five years, the unit of difference for agency life-cycle costs is \$1,000 and five tonnes for CO<sub>2</sub>e. For the user life-cycle costs and emissions a similar tact of worst-case scenario is considered. However, in this case it doesn't make sense to normalize to a centimeter of overlay thickness. User life-cycle costs and GHG emissions are a function of the pavement roughness and not overlay thickness. A maximum Overlay Interval of 25 years is assumed, which will produce the roughest pavements possible. Thus, for the I-80 case, the meaningful unit of difference is \$35,000 and ten tonnes for CO<sub>2</sub>e. For SR-13 case, the meaningful unit of difference is \$6,000 and three tonnes for CO<sub>2</sub>e. Then taking the maximum values for each case, for I-80 the values remain the same, but for SR-13 they are now \$6,000 and five tonnes of CO<sub>2</sub>e.

## 5 Discussion

### 5.1 Contributions

A feasible analytical framework was developed that makes use of an infinite planning horizon, which quantifies the tradeoffs, if any, between saving life-cycle costs or GHG emissions. These quantities are shown on Decision Curves that have the perspective of total life-cycle costs as well as agency and user costs juxtapositioned with total GHG emissions. Each Decision Curve contains within it a sub-region, bounded on one side by the total life-cycle cost minimum and on the other by the total GHG emissions minimum, that is a Pareto frontier. The Pareto frontier represents a special interval where changes in pavement management policy that save costs will come at the expense of increased GHG emissions or similarly changes that save GHG emissions will come at the expense of some costs. Locations on the Decision Curve that are outside of the Pareto frontier sub-interval present more trivial situations for decision makers in that changes that bring savings in costs will also bring savings in GHG emissions. Thus, the sub-interval that is the Pareto frontier is the region of particular interest.

Each point of the Pareto frontier on a Decision Curve represents an optimal pavement management policy. Each point is an optimal since no improvement can be made to improve both life-cycle costs and GHG emissions on the Pareto frontier. Thus, a tradeoff is required. Each point on the Pareto frontier also corresponds to a market value of CO<sub>2</sub>. Conversely, each market value for CO<sub>2</sub> is represented on the Pareto frontier as the cost minimum corresponds to zero dollars per tonne of CO<sub>2</sub>e saved, and the GHG emissions minimum corresponds to an infinite number of dollars per tonne of CO<sub>2</sub>e saved. As these two minimum points determine the endpoints of the Pareto frontier, all possible market values are represented. Thus, if a market value for CO<sub>2</sub> exists, the point with the negative of the slope of its tangent line that equals this market value defines a unique optimal pavement management policy.

With proposed changes in pavement management policy are associated cost-effectiveness values that quantify the cost of a unit of GHG emissions saved (\$/tonne CO<sub>2</sub>e saved). These quantified values will allow decision makers to compare the proposed pavement management policy change to other GHG emission saving policies such as installing insulation in all public buildings or mandating low-carbon fuels. For policy changes that occur on the Decision Curve but strictly outside the Pareto frontier, any savings in GHG emissions will also save life-cycle costs and the cost-effectiveness value will be negative. For policy changes that involve points within the Pareto frontier, there may be a cost associated with GHG emission savings and thus the cost-effectiveness value will be positive. At any rate, the cost-effectiveness value will equal the negative of the slope of the secant line through the current pavement management policy and the proposed policy. The Decision Curve also shows that, if operating within the Pareto frontier, in order to increase the total amount of GHG emissions saved, the cost per unit of emissions will also increase (negative of slope of secant line increases). Thus, the more emissions saved, the more it will cost to save.

The Decision Curves can further assist an agency in that current practices, whatever they are, exist on the curve. Thus, decision makers can see how a change in pavement management policy from their current behavior will either cost or save society money, or the agency, or the users. As GHG emissions are also on the Decision Curve, an estimated amount of emissions savings or gains is shown. This provides a tool for decision makers currently not available.

The sensitivity analysis has revealed that some parameter input values cause more uncertainty than others. For example, consistent with previous findings (Li and Madanat 2002), pavement deterioration models do have an effect on outcomes, but when uncertainty is within 20%, these changes are not large. However, VMT growth had a large effect on total emissions due to both the number of vehicle miles contributing to fuel consumption and costs, but also since the pavement will deteriorate more quickly from the increased traffic loads.

Additionally, even if no certainty is afforded quantification outcomes, the sensitivity analysis indicates trends due to changes in input parameters. For example, if vehicle fuel economy is improved, there will be a savings in overall emissions and user costs, but the roadways will be allowed to become rougher in order to realize the emissions savings. This is an unexpected negative adverse event from increased vehicle fuel economy. A similar analysis showed that reducing the emissions associated with asphalt overlay application can counteract the effects of the vehicle fuel economy improvements and thus reduce roadway roughness at the emissions optimal. Since the vehicle fuel economy improvements are expected through market or regulatory forces, research investments in improved overlay technologies is paramount to counteract the negative side effects of the improved fuel economies and keep the pavements from being rougher.

The sensitivity analysis also revealed that by changing some parameter input values, the total life-cycle costs and total GHG emission minimum policies could be brought to match each other. For example, by reducing the emissions associated with the asphalt overlay process but not changing the costs, the cost optimal and the GHG emissions optimal (for one of the case studies) were achieved by the same Overlay Interval. This would make optimizing for emissions much easier as data on costs are much more easily available to agencies than emissions data. Further, making the two points of optimality the same essentially makes all points on the Decision Curve outside of the Pareto frontier, and thus, all efforts to save money will also result in saving emissions.

The sensitivity analysis also revealed how climate change policies could influence the pavement management strategies as several changes in input parameters corresponded with potential policies. For example, the above-mentioned reductions in overlay application emissions could be accomplished from increased research funding for cold-mix asphalt technologies. This new process does not cost much less, but has been shown to have significant reductions in associated GHG emissions for the application of asphalt overlays (Thenoux et al. 2007).

Conversely, climate change policy changes can be evaluated directly by altering input parameters of the model to fit the new policy specifics. Thus, the new analytical framework for optimizing for both costs and emissions is useful in evaluating both actual and proposed political policies. For example, the new federal CAFE standards imposed recently in combination with the new heavy-duty truck standards have the potential to save only 1% on costs (since savings on fuel consumption are such a small percentage of total costs associated with a roadway), but 12% on emissions (for year 2018 on I-80 case study).

## ***5.2 Recommendations for Implementation***

To utilize the developed analytical framework going forward, it is imperative that a state agency implements some data collection processes that systematically keep a detailed pavement segment database current. The data collection process should maintain accurate estimates for

each pavement segment in the state: VMT by vehicle type, ESALs (traffic loading), pavement roughness (IRI), pavement structural number (design quality), and complete rehabilitation and maintenance history (costs and specifications). It would be important for maintenance and rehabilitation histories to have a supplemental record that is detailed enough to estimate GHG emissions associated with each activity. Also, before and after rehabilitation activities, roughness values should be collected and recorded. Caltrans is currently developing these systems, but does not yet have any detailed system in place. Further, the state agency should also have accurate data on the average fuel economy of each vehicle type, and tracked fuel prices for each type of transportation fuel.

If each of the above data points can be maintained accurately on an ongoing basis, then a state agency can more accurately make use of the developed analytical framework and have even more reliable estimates of costs, GHG emissions, and their related optimal management policies. In addition, more specific pavement deterioration and pavement improvement models could easily be maintained that are specific to the particular state and much more accurate. The estimated input parameters, for these models, can be updated using a Bayesian algorithm ensuring that the more data collected over time, the more accurate the models and resulting estimates become. Similarly, the cost and GHG emission estimates used in the models could be updated annually with better estimates each time. As technologies change for both users and agencies, the changing costs and emissions will be automatically incorporated in the database. This is particularly important as much of the uncertainty associated with the entire analytical framework largely comes from the points listed in this paragraph.

The components listed above along with the developed analytical framework are the key components of a PMS that includes emissions in addition to costs as an optimization criterion. Such a PMS should be rendered and implemented as soon as possible for immediate cost and emission savings. The PMS should track total costs, agency costs, and user costs as well as the emissions counterparts. The PMS should generate Decision Curves as done herein for maximal utility to decision makers.

The completed research lays the groundwork for the network version of the optimization process. At this time, no network optimization has been developed that incorporates both costs and emissions. Future work will produce this network level optimization framework and demonstrate feasibility. Then, the PMS can also be optimized over networks or districts within the state to mirror budget allocation procedures. In this way, the PMS will inform a state agency exactly how to alter their current pavement management strategies to save exactly how much GHG emissions at whatever cost they are comfortable with. If there is an emissions budget or if there is a market value for CO<sub>2</sub>e, then a unique management policy is identified. The cost of rendering such a PMS and maintaining a large associated database will be considerable, but insignificant as compared to the savings the resulting system will afford the state. The state of Arizona saved \$14 million in their first year of using a PMS (Golabi et al. 1982) and the budget for Arizona's highway system is much smaller than California's.

### **5.3 Limitations**

The developed analytical framework generally performs as expected in that it is adaptable to various roadway segments in terms of traffic loading, deterioration rate, and durability. It



accommodates different fuel economy assumptions, costs, and emission rates. This allows for wide applicability to most particular pavement segments.

However, there are also a few shortcomings of the developed model. The extent to which the framework is generalizable is limited. The current analysis does not account for initial pavement capital costs, environmental effects of pavement deterioration, or goods damage. Costs of maintenance and tires are accounted for, but not their associated emissions. Emissions due to traffic delays caused by pavement overlay application were not accounted for since Caltrans typically performs these activities during nighttime hours when there is little traffic in major metropolitan areas such as the San Francisco Bay Area and the greater Los Angeles region. Emission savings due to roughness-induced traffic speed reductions were not accounted for as little data were available and no justification for North America was found. There is plenty of evidence that extremely rough roads such as unpaved roads in poor condition have an effect on traffic speed (Paterson, 1987), but this situation is not typical of California state highways or other state highways in the United States with significant levels of traffic. Although a distribution of truck types was used to estimate the ESALs for pavement deterioration, only a single average heavy-duty truck or “representative truck” was used to estimate fuel usage and susceptibility to roughness.

## **5.4 Future Work**

The logical next step for this research is to expand this single facility optimization to a network. A network optimization would require the assumption of either a cost budget or an emissions budget and then perform the optimization with respect to the budget. Data requirements of a network optimization include pavement traffic loadings and design specifications for each pavement segment of the network. These data requirements are not available at this time and precluded the ability to do the network optimization at this time. Research is concurrently being conducted to develop better LCA estimates for pavement supply chain emissions and costs specific to California. In addition, improved estimates for pavement segment ESALs (pavement loadings) and structural numbers (design level) are being finalized for the entire state of California. These exact input values are required to expand the facility level analysis developed here to the California network. A network optimization method developed by Sathaye and Madanat (2011) and refined in Sathaye and Madanat (2012) can be utilized to optimize California networks subject to either a cost or an emissions budget. This work will allow for estimating the emissions savings potential of applying an optimal pavement rehabilitation policy to the entire state of California.

## **5.5 Conclusions**

The general framework for optimizing pavement rehabilitation policy developed in this study should be a useful tool for decision makers who want to understand the tradeoffs between costs and GHG emissions. The cost per ton of CO<sub>2</sub>e saved can be inferred directly from the Pareto frontiers providing policy makers with information useful in comparing pavement maintenance strategies for emissions reductions to other strategies. Since results are shown delineated by User Costs, Agency Costs, and their sum (Total Costs), decision makers can deduce the dollars per tonne of CO<sub>2</sub>e saved for each cost component for each year the pavement overlay interval is changed. Similarly, emission totals delineated by User and Agency Emissions indicate under what circumstances each source of emission dominates the other. If a market

value for carbon exists, then this analytical framework will define a unique optimal rehabilitation policy that balances life-cycle costs and GHG emissions.

Case studies for a two-lane arterial and a ten-lane major highway in California are presented when traditional hot-mix asphalt overlays are applied. The 2011 case studies are particular to California by traffic loadings and pavement durability. However, the user and agency emissions and costs estimations are based on national data. Thus, generalizability of the case study results are subject to these caveats. An ordinary medium-volume metropolitan state highway and an extremely heavily traveled highway bearing commuters into San Francisco are optimized to represent, with only two examples, a breadth of situations.

Results for a one-kilometer segment of Interstate-80, in Berkeley California, with ten lanes and 273,000 light-duty vehicles and 13,100 heavy-duty vehicles per day, indicate that the life-cycle cost minimum occurs when asphalt overlays are applied every 15 years or equivalently when the pavement roughness reaches an international roughness index (IRI) of 2.7 m/km. Coincidentally, this is the same roughness Caltrans uses to decide when to apply an overlay for the entire state. However, where any of the conditions or characteristics for any pavement segments are different, the coincidence may cease. The minimum life-cycle cost at this optimal pavement rehabilitation strategy is approximately \$490,000 per kilometer per year, at which point resurfacing activity and user vehicles would emit approximately 220 tonnes of CO<sub>2</sub> equivalents per kilometer per year. The GHG emissions minimum corresponds to an overlay interval of 22 years or the equivalent threshold roughness IRI of 3.4 m/km. The minimum GHG emissions are approximately 200 tonnes of CO<sub>2</sub> equivalents per kilometer per year, with life-cycle costs at approximately \$520,000 per kilometer per year.

Any pavement rehabilitation strategy that makes use of overlay intervals outside of this sub-interval defined by the life-cycle cost and GHG emissions optima are trivial in that any strategy change designed to reduce costs also reduces emissions. However, inside this special sub-interval, any change in strategy that reduces costs will increase emissions and vice versa. Thus, this special sub-interval constitutes a Pareto frontier of optimal solutions where tradeoffs are associated with each change. For example, if Caltrans is currently operating at the life-cycle cost minimum by applying an overlay interval every 15 years and they decide to reduce emissions by changing to every 18 years, there will be a reduction in emissions. However, it will come at a total life-cycle cost such that the cost-effectiveness ratio of such a change is approximately \$500 per tonne of CO<sub>2</sub> equivalents. Of course, different pavement rehabilitation strategy changes will present different cost-effectiveness ratios. If the change spans points outside the Pareto frontier, the costs may be minimal or even negative. However, within the Pareto frontier, attempts to save even more emissions will increase costs per unit of CO<sub>2</sub> equivalents saved.

The sensitivity analysis allows for further policy analysis that is flexible enough to accommodate a wide range of potential policies. Further, the flexibility of the analysis framework allows for application to a wide range of pavement locations and traffic uses.

Results of the sensitivity analysis indicate that minimum achievable roughness, deterioration rates, vehicle fuel economy, and overlay emissions all affect life-cycle costs and GHG emissions. Improved fleet fuel economy will save both life-cycle costs and GHG emissions, but may induce rougher roads as a byproduct. Investing in more durable pavements leads to slower deterioration and reduces life-cycle costs and GHG emissions. Development of new overlay technologies that reduce both emissions and costs associated with rehabilitation

activities reduces costs, emissions, and pavement roughness. Thus, new overlay technologies emerge as a priority specifically to offset the improvements in fleet fuel economy and their associated higher trigger roughnesses anticipated in the future. The number of lanes requiring overlay, minimum achievable roughness, and traffic loadings can interact to change whether a smoother pavement reduces or increases total GHG emissions. For life-cycle costs, the lower minimum achievable roughness is always best. This result underscores the fact that optimizing for life-cycle costs does not always optimize for GHG emissions as well. These results have important implications for developing countries where new road construction is more prevalent.

As some pavement rehabilitation strategy changes have associated cost-effectiveness ratios that are negative, many proposed changes will save both life-cycle costs and GHG emissions. However, changes that are within the Pareto frontier sub-section of the decision curves will have costs associated with GHG emission savings. Many of these costs are large relative to the current market rates of carbon in Europe. It is possible that by reducing the overall life-cycle costs and GHG emissions, through efficiency efforts, that the system will enable lower cost-effectiveness ratios to be more common. However, it is more likely that with the California cap-and-trade program coming in January 2013, that the market value of carbon will reach much higher levels. At some point, Caltrans may be able to offset the additional cost of saving GHG emissions by selling carbon credits to those who need to buy them. The price gained for the credits need not pay for the entire cost of the emissions but perhaps mitigate the costs enough for decision makers to justify the cost of the carbon savings. This use of market value for carbon to enable more emissions savings is exactly the intent of the cap-and-trade legislation.

## 6 References

- American Society for Testing and Materials (ASTM). (1982). *Standard Definitions of Terms Relating to Traveled Surface Characteristics*. ASTM Standard E867 – 82A. Philadelphia.
- American Society of Civil Engineers (ASCE). (2009). “Report Card for America’s Infrastructure” <<http://apps.asce.org/reportcard/2009/grades.cfm>> (March 1, 2011).
- Assembly Bill No. 32. (2006). “California Global Warming Solutions Act of 2006”. Division 25.5 of the California Health and Safety Code.
- Au T., and Au T.P. (1992). “Engineering Economics for Capital Investment Analysis”, Prentice-Hall, Inc., Englewood Cliffs, New Jersey 07632, 71-74.
- Barnes G., and Langworthy, P. (2004). Per Mile Costs of Operating Automobiles and Trucks. *Transportation Research Record: Journal of the Transportation Research Board, No. 1864*, TRB, National Research Council, Washington, D.C., 71-77.
- Bureau of Transportation Statistics (2006). “National Transportation Statistics: Table 4-23: Average Fuel Efficiency of U.S. Passenger Cars and Light Trucks.” *Research and Innovative Technology Administration (RITA). U.S. Department of Transportation*. <[http://www.bts.gov/publications/national\\_transportation\\_statistics/html/table\\_04\\_23.html](http://www.bts.gov/publications/national_transportation_statistics/html/table_04_23.html)>. (July 16, 2009).
- Bureau of Transportation Statistics (2011a). “National Transportation Statistics: Table 1-11: Number of U.S. Aircraft, Vehicles, Vessels, and Other Conveyances”. *Research and Innovative Technology Administration (RITA). U.S. Department of Transportation*. [http://www.bts.gov/publications/national\\_transportation\\_statistics/html/table\\_01\\_11.html](http://www.bts.gov/publications/national_transportation_statistics/html/table_01_11.html) (October 25, 2011).
- Bureau of Transportation Statistics (2011b). “National Transportation Statistics: Table 1-37: U.S. Passenger Miles”. *Research and Innovative Technology Administration (RITA). U.S. Department of Transportation*. [http://www.bts.gov/publications/national\\_transportation\\_statistics/2006/html/table\\_01\\_37.html](http://www.bts.gov/publications/national_transportation_statistics/2006/html/table_01_37.html) (October 25, 2011).
- Caltrans (2007a). “State of the Pavement, 2007”. *Report by the State of California Department of Transportation, Division of Maintenance*. <[www.dot.ca.gov/hq/maint/2007\\_SOP\\_8\\_7\\_08.pdf](http://www.dot.ca.gov/hq/maint/2007_SOP_8_7_08.pdf)> (March 17, 2011).
- Caltrans (2007b). “Life-cycle Cost Analysis Procedures Manual”. *Report by the State of California Department of Transportation, Pavement Standards Team & Division of Design*.
- Caltrans (2008). “2008 Annual Average Daily Truck Traffic on the California State Highway System”. *Report by State of California, Business Transportation and Housing Agency, Department of Transportation*. <<http://traffic-counts.dot.ca.gov/truck2008final.pdf>> (March 1<sup>st</sup>, 2010).
- Caltrans (2009). “California Highway Design Manual - Chapter 630”. *California Department of Transportation, Publication Distribution Unit*. <<http://www.dot.ca.gov/hq/oppd/hdm/hdmtoc.htm>>. (June 17, 2010).

- CARB (2012). "California Air Resources Board Cap-and-Trade Program". *California Environmental Protection Agency*.  
<<http://www.arb.ca.gov/cc/capandtrade/capandtrade.htm>> (March 11, 2012).
- Carey, W.N., and Irick, P.E. (1960). "The Pavement Serviceability Performance Concept". *Highway Research Bulletin* 250 Highway Research Board, Washington, D.C., 40-58.
- Carnahan, J.V., Davis, W.J., Shahin, M.Y., Kean, P.L., and Wu, M.I. (1987). "Optimal Maintenance Decisions for Pavement Management". *Journal of Transportation Engineering*, 113(5), 554-572.
- CEC (2007). "Full Fuel Cycle Assessment: Well-to-wheels Energy Inputs, Emissions, and Water Impacts." *California Energy Commission*, CEC-600-2007-004-REV, Sacramento, California.
- Chester, M.V., and Horvath A. (2009). "Environmental Assessment of Passenger Transportation Should Include Infrastructure and Supply Chains". *Environmental Research Letters*, 4, 024008.
- Chiu, C., Hsu, T., Yang, W. (2007). "Life Cycle Assessment on Using Recycled Materials for Rehabilitating Asphalt Pavements". *Resources, Conservation and Recycling*, 52, 545-556.
- Cleveland, G.S., Button, J.W., and Lytton, R.L. (2002). "Geosynthetics in Flexible and Rigid Pavement Overlay Systems to Reduce Reflection Cracking". *Texas Department of Transportation Report #1777-1*, College Station, TX.
- Cline, W.R. (2004). "Meeting the challenge of global warming." In: Lomborg, B (Ed.), *Global Crises, Global Solutions*. Cambridge University Press, Cambridge, 13-43.
- Daganzo C.F. (2005). "Logistics Systems Analysis". Springer-Verlag Berlin Heidelberg, Germany.
- Deluchi, M.A. (1991). "Emissions of Greenhouse Gases from the Use of Transportation Fuels and Electricity". *Report by Center for Transportation Research, Energy Systems Division, Argonne National Laboratory*, Argonne, Illinois.
- Energy Information Agency (2011). "Gasoline and Diesel Fuel Update".  
<<http://www.eia.gov/oog/info/gdu/gasdiesel.asp>> , (February 2, 2011)
- Environmental Protection Agency (EPA). (2005). "Emission Facts: Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel". *Office of Transportation and Air Quality*. EPA420-F-05-001, February.  
<<http://www.epa.gov/otaq/climate/420f05001.htm>>. (July 15<sup>th</sup>, 2010).
- Environmental Protection Agency (EPA). (2011). "2017-2025 Model Year Light-Duty Vehicle GHG Emissions and CAFE Standards: Supplemental Notice of Intent". National Highway Traffic Safety Administration 49 CFR Parts 531 and 533, Environmental Protection Agency 40 CFR Parts 85, 86, and 600.
- Federal Highway Administration (FHWA). (2007). "Highway Statistics 2007".  
<<http://www.fhwa.dot.gov/policyinformation/statistics/2007>>. (April 3rd, 2009).
- Friesz, T.L., and Fernandez, J.E. (1979). "A model of optimal transport maintenance with demand responsiveness". *Transportation Research Part B*, 13, 317-339.

- Gillespie, J.S., and McGhee, K.K. (2007). "Get In, Get Out, Come Back!: What the Relationship Between Pavement Roughness and Fuel Consumption Means for the Length of the Resurfacing Cycle". *Journal of the Transportation Research Record*, No. 1990, Transportation Research Board of the National Academies, Washington, D.C. 32-39.
- Golabi, K., Kulkarni, R., and Way, G. (1982). "A Statewide Pavement Management System". *Interfaces*, 12(6), 16-31.
- Guo, J., Hepburn, C.J., Tol, R.S.J., and Anthoff, D. (2006). "Discounting and the Social Cost of Carbon: a Closer Look at Uncertainty". *Environmental Science and Policy*, 9, 205-216.
- Hepburn, C. (2006). "Valuing the Far-off Future: Discounting and its Alternatives." In: Atkinson, G., Dietz, S., Neumayer, E. (Eds.), *Handbook of Sustainable Development*, Edward Elgar, Cheltenham, UK.
- Hong, F. and Prozzi J.A. (2006). "Estimation of Pavement Performance Deterioration Using Bayesian Approach". *Journal of Infrastructure Systems*, 12(2), 77-86.
- Janoff, M.S., Nick, J.N., Davitt, P.S., and Hayhoe, G.F. (1985). "Pavement Roughness and Rideability". *National Cooperative Highway Research Program, Report 275*. Transportation Research Board, Washington, D.C.
- Kendall, A., Harvey, J., and Lee, I. (2009a). "A Critical Review of Life Cycle Assessment Practices for Infrastructure Materials" Proceedings of US-Japan Workshop on Life Cycle Assessment of Sustainable Infrastructure Materials, Sapporo Japan, October 21-22.
- Kendall, A., Chang, B., and Sharpe, B. (2009b). "Accounting for Time-Dependent Effects in Biofuel Life Cycle Greenhouse Gas Emissions Calculations". *Environmental Science Technology*, 43, 7142-7147.
- Knittel, C., and Sandler, R. (2011). "Cleaning the Bathwater with the Baby: The Health Co-Benefits of Carbon Pricing in Transportation" *Energy Institute at Haas Working Paper Series, WP 219*. University of California Energy Institute at Haas, Berkeley, CA.
- Ksaibati and Mahmood (2002). Utilizing the Longterm Pavement Performance Database in Evaluating the Effectiveness of Pavement Smoothness. Unpublished report to US DOT.
- Li, Y., and Madanat, S. (2002). "A steady-state solution for the optimal pavement resurfacing problem". *Transportation Research Part A*. 36, 525-535.
- Lutsey, M., and Sperling, D. (2009). "Greenhouse Gas Mitigation Supply Curve for the United States for Transport Versus Other Sectors". *Transportation Research Part D: Transport and Environment*, 14(3), 222-229.
- Madanat, S., Prozzi, J.A., and Han, M. (2002). "Effect of Performance Model Accuracy on Optimal Pavement Design". *Computer-Aided Civil and Infrastructure Engineering*, 17, 22-30.
- Markow, M., and Balta, W. (1985). "Optimal Rehabilitation Frequencies for Highways Pavements". *Transportation Research Record 1035*, 31-43.
- Muench S.T., Mahoney, J.P., Wataru, W., Chong, L., and Romanowski, J. (2007). "Best Practices for Long-lasting Low-volume Pavements". *Journal of Infrastructure Systems*, 13(4), 311-320.

- New York Times (2010). “New Truck Emission Standards Receive Wide Praise”. By Jim Motavalli of the New York Times, New York.  
<http://wheels.blogs.nytimes.com/2010/10/27/new-truck-emission-standards-receive-wide-praise/> (October the 25<sup>th</sup>, 2011).
- O’Hare, M., Plevin, R.J., Martin, J.I., Jones, A.D., Kendall, A., and Hopson, E. (2009). “Proper accounting for time increases crop-based biofuels’ greenhouse gas deficit versus petroleum”. *Environmental Research Letters*, 4. <doi:10.1088/1748-9326/4/2/024001>
- Ouyang, Y., and Madanat, S. (2004). “Optimal Scheduling of Rehabilitation Activities for Multiple Pavement Facilities: Exact and Approximate Solutions”. *Transportation Research Part A*, 38, 347-365.
- Ouyang, Y., and Madanat, S. (2006). “An Analytical Solution for the Finite-horizon Pavement Resurfacing Planning Problem”. *Transportation Research Part B*, 40(9), 767-778.
- Paterson, W. (1987). “Road Deterioration and Maintenance Effects: Models for Planning and Management”. Published for The World Bank. The Johns Hopkins University Press.
- Prozzi, J.A., and Madanat, S.M. (2004). “Development of Pavement Performance Models by Combining Experimental and Field Data”. *Journal of Infrastructure Systems*, ASCE, 10(1), 9-22.
- Rajendran, S. and Gambatese, J.A. (2007). “Solid Waste Generation in Asphalt and Reinforced Concrete Roadway Life Cycles”. *Journal of Infrastructure Systems*, ASCE, 13(2), 88-96.
- Santero, N.J., and Horvath, A. (2009). “Global Warming Potential of Pavements”. *Environmental Research Letters*, 4, 034011.
- Sathaye, N., Horvath, A., and Madanat, S. (2010). “Unintended Impacts of Increased Truck Loads on Pavement Supply-chain Emissions”. *Transportation Research Part A*, 44, 1-15.
- Sathaye, N., and Madanat, S. (2011). “A Bottom-up Solution for the Multi-facility Optimal Pavement Resurfacing Problem.” *Transportation Research Part B*, 45, 1004-1017.
- Sathaye, N., and Madanat, S. (2012). “A Bottom-up Solution for the Multi-facility Optimal Pavement Resurfacing Solution Approach for Large-scale Networks.” *Transportation Research Part B*, 46, 520-528.
- Sayers, M.W., Gillespie, T.D., and Queiroz, C. A. (1986). “The International Road Roughness Experiment”. World Bank Technical Paper Number 45. The World Bank, Washington, D.C.
- Schuring, D.J. (1988). “Tire Rolling Loss—An Overview,” Presented at the Seventh Annual Meeting and Conference on Tire Science and Technology, Akron, Ohio.
- Slaughter, G. (2004). “Environmental Comparison of Cutback Bitumen and Bitumen Emulsions for Sealing Roads”. 10<sup>th</sup> Australian Flexible Pavements Industry Conference on Health, Safety & the Environment.
- Small, K.A., Winston, C., and Evans, C.A. (1989). “Road Work: A New Highway Pricing & Investment Policy”. The Brookings Institution, Washington, D.C.
- Sperling, D., and Gordon, D. (2009). “Two Billion Cars – Driving Toward Sustainability”. Oxford University Press, New York, N.Y.

- Thenoux, G., Gonzalez, A., and Dowling, R. (2007). "Energy Consumption Comparison for Different Asphalt Pavements Rehabilitation Techniques Used in Chile". *Resources, Conservation and Recycling*, 49(4), 325-339.
- Transportation Research Board (TRB). (2006). "Special Report 286: Tires and Passenger Vehicle Fuel Economy", National Research Council.
- Tsunokawa, K., and Schofer, J.L. (1994). "Trend Curve Optimal Control Model for Highway Pavement Maintenance: Case Study and Evaluation". *Transportation Research Part A*, 28, 151-166.
- Wang, M. (2002). "Fuel Choices for Fuel-cell Vehicles: Well-to-wheels Energy and Emission Impacts". Argonne National Laboratory. *Journal of Power Sources*, 112, 307-321.
- Watanatada, T., Dhareshwar, A.M., and Lima, P.R.S.R. (1987). "Vehicle Speeds and Operating Costs: Models for Road Planning and Management". Published for The World Bank. The Johns Hopkins University Press.
- Watson, D.E., and Moore, J.R. (2011). "Evaluation of SMA Mixture with iBind and Fibers". *National Center for Asphalt Technology Report #11-04*, Auburn, AL.
- Zaabar, I., and Chatti, K. (2010). "Calibration of HDM-4 Models for Estimating the Effect of Pavement Roughness on Fuel Consumption for U.S. Conditions". *Transportation Research Record: Journal of the Transportation Research Board*, No. 2155, Transportation Research Board of the National Academies, Washington, D.C., 105–116.
- Zhang, H., Lepech, M.D., Keoleian, G.A., Qian, S., and Li, C.V. (2010a). "Dynamic Life Cycle Modeling of Pavement Overlay Systems: Capturing the Impacts of Users, Construction, and Roadway Deterioration". *Journal of Infrastructure Systems*, ASCE, 16(4), 299-309.
- Zhang, H., Keoleian, G.A., Lepech, M.D., and Kendall, A. (2010b). "Life Cycle Optimization of Pavement Overlay System". *Journal of Infrastructure Systems*, ASCE, 16(4), 310-322.