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The Effect of Agency Budgets on Minimizing Greenhouse Gas Emissions from Road Rehabilitation Policies

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Abstract

Transportation agencies are being urged to reduce their greenhouse gas (GHG) emissions. One possible solution within their scope is to alter their pavement management system to include environmental impacts. Managing pavement assets is important because poor road conditions lead to increased fuel consumption of vehicles. Rehabilitation activities improve pavement condition, but require materials and construction equipment, which produce GHG emissions as well. The agency's role is to decide when to rehabilitate the road segments in the network. In previous work, we sought to minimize total societal costs (user and agency costs combined) subject to an emissions constraint for a road network, and demonstrated that there exists a range of potentially optimal solutions (a Pareto frontier) with tradeoffs between costs and GHG emissions. However, we did not account for the case where the available financial budget to the agency is binding. This letter considers an agency whose main goal is to reduce its carbon footprint while operating under a constrained financial budget. A Lagrangian dual solution methodology is applied, which selects the optimal timing and optimal action from a set of alternatives for each segment. This formulation quantifies GHG emission savings per additional dollar of agency budget spent, which can be used in a cap-and-trade system or to make budget decisions. We discuss the importance of communication between agencies and their legislature that sets the financial budgets to implement sustainable policies. We show that for a case study of California roads, it is optimal to apply frequent, thin overlays as opposed to the less frequent, thick overlays recommended in the literature if the objective is to minimize GHG emissions. A promising new technology, warm-mix asphalt, will have a negligible effect on reducing GHG emissions for road resurfacing under constrained budgets.

Introduction

The United States has recently set an ambitious target of reducing greenhouse gas (GHG) emissions by 26-28% below 2005 levels by 2025 (White House 2015), and similar or longer-term goals are being adopted or discussed worldwide. Significant actions have been taken thus far, such as investing in clean power and setting energy and fuel efficiency standards, but more investments are needed. Reducing GHG emissions will require cooperation and willingness from decision-makers across all economic sectors, especially those with the largest contributions. The transportation sector accounts for large emissions worldwide; 28% of the total GHG emissions in the United States, most of which comes from the tailpipes of vehicles (EPA 2014).

Transportation infrastructure is typically not included in the sector's account, therefore the overall transportation sector's impact is even higher (Chester and Horvath 2009, Revi 2014).

In 2014, there were over 4.8 trillion vehicle kilometers traveled (VKT) on 6.3 billion lane kilometers of roads (FHWA 2014, Census Bureau 2014) in the United States. The agencies responsible for the care and maintenance of the most traveled roads, state departments of transportation (DOTs), are being urged to reduce their carbon footprints. This is driven by desire to assist with reaching the national target, public pressure to be more sustainable, and state emissions goals set into law (e.g., Assembly Bill 32 in California) (Air Resources Board 2014). There is untapped potential within an agencies' scope, which could bring additional significant reductions (Sathaye 2010, Horvath and Hendrickson 1998, Cicas 2007, Santero 2011*a*, Santero 2011*b*). In this letter, the focus is on the potential GHG emission reductions from new rehabilitation policies.

Transportation agencies have two options for each road segment at any given point in time: they can elect to do nothing, or they can perform a rehabilitation action. If they elect to do nothing, the pavement condition worsens. Roughness has been identified as the most important indicator of performance and will be used as the measure of pavement condition in this letter (FHWA 2012). It is a measure of the unevenness of the road along the longitudinal profile in the wheelpath and is measured by the international roughness index (IRI) in m/km. As roughness increases, fuel consumption also increases, resulting in greater emissions from the tailpipes of vehicles (Watanatada 1987). To keep the user emissions down, agencies can perform a rehabilitation action such as a resurfacing, which improves the condition of the road. While effective in reducing user emissions, rehabilitation actions result in large quantities of GHG emissions being released into the atmosphere from the manufacturing and transporting of the materials and the construction stage (Santero and Horvath 2009). There is optimal timing to perform rehabilitation where the combined user and agency emissions for that segment are minimized (Reger 2014). In theory, an agency would always choose to rehabilitate at that timing, but in practice, there are other factors that can interfere. The agency chooses the action and time, but the total budget they have is beyond their control. A binding financial budget can force the agency to rehabilitate the roads in the network with less frequency than would be optimal.

Multi-objective optimization has been identified as an effective technique for infrastructure management problems (Wu 2012). In Reger et al. (2014), we solved a multi-facility, continuous time, continuous state, infinite horizon problem for a heterogeneous pavement network. We sought to minimize total societal costs (user and agency combined) subject to an emissions constraint, giving a range of potentially optimal policies that could be applied by the agency. For this range of potentially optimal solutions, an agency cannot reduce total costs without increasing GHG emissions, nor reduce GHG emissions without increasing costs, creating a Pareto frontier. Network-level Pareto-optimal solutions have been applied to pavement management previously, but have focused on aspects such as cost, performance, condition, and work production (Bai 2011, Bai 2014, Bryce 2014, Fwa 2000, Sathaye and Madanat 2012). Wang et al. 2012 and

Wang et al. 2014 examined the case of optimizing with respect to environmental considerations and energy at a network level. There has been research that has examined simultaneously optimizing costs and greenhouse gas emissions but did not include Pareto optimality (Zhang 2010) or focused on material comparison (Zhang 2013). At a single project level, the Pareto frontier between costs and GHG emissions was previously examined (Lidicker 2014). At a network level, Pareto optimality was examined by Gosse et al. (2012), but did not include the GHG effects from user vehicles caused by changes in pavement condition.

The potentially optimal policies from Reger et al. (2014) assumed unlimited financial resources for the agency. This is not typically the case in practice. In this letter we take a different perspective, examining the case of an agency which seeks to reduce its GHG emissions when the budget that can be spent on rehabilitation in a given year is limited. We show that achieving a financially sustainable and low-carbon pavement management system requires cooperation between legislators and transportation agencies. It is the responsibility of the agency to properly use the budget they are supplied with, but it is the responsibility of the legislation to provide the agency with sufficient funding to apply a policy which reduces their global warming impacts. There needs to be a combined effort to ensure that tax money is allocated properly to achieve the largest reductions in GHG emissions.

The methodology used in Reger et al. (2014) is modified to become more applicable for real-life scenarios. That paper considered a single type of rehabilitation activity, but state agencies have many options at their disposal. We show how to compare these different rehabilitation options, while still maintaining the Lagrangian dual formulation which allows for efficient solutions for large-scale networks. Using this new approach, the optimal activity and the optimal timing are chosen for each road segment in the network. We show that the results are robust to uncertainty in the deterioration rate, best achievable roughness level, and effect of roughness on fuel consumption. We also examine the potential effects of using warm-mix asphalt as a material in pavement resurfacing.

Problem Formulation

As in Reger et al. (2014), we use a continuous time, continuous state, infinite-horizon optimization formulation. The problem is formulated as an objective function subject to two constraints, as shown in Equations 1-3. Equation 1, the objective function, is the sum of the total yearly emissions, Q_{jk}, for all facilities j=1,…,J, choosing from potential rehabilitation actions, k=1,…,K. Q_{jk} includes the user emissions, W_{jk}, and the agency emissions associated with applying the rehabilitation action, A_{jk}. W_{jk} is an integral from 0 to τ and A_{jk} is a function of the number of lanes of the roadway and the chosen action, k. τ_{jk} is the decision variable, and is the interval of action k for segment j. Emissions are annualized by dividing by τ, since there is no scientific consensus on a discount rate (Sedjo and Marland 2003). Equation 2 is the budget constraint, where M_{jk} is the cost of action k for segment j and B is the annual budget. Budget values are not discounted as this is meant to represent the necessary budget per time and also helps to capture the idea of an agency having a multi-year budget. The final constraint bounds the potential solutions between 0 and τ_{jk}^{e} (the optimal timing where total emissions are minimized). Note that τ cannot equal 0, as it would render the objective function undefined.

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

$$\text{s.t.} \; \sum_{j=1}^{J}\left\{\mathrm{M}_{jk}(\tau_{jk})\left(\frac{1}{\tau_{jk}}\right)\right\} \leq B \qquad \text{Eq(2)}$$

$$\tau_{jk} \in (0, \tau_{jk}^{e}] \qquad \text{Eq(3)}$$

The scope of roughness considered for user emissions is shown in Figure 1. The emissions associated with roughness below the best-achievable level after rehabilitation are beyond the control of the agency. Therefore, these emissions are not included in the optimization. However, different rehabilitation actions have different best-achievable levels of roughness. S_1^* is the best-achievable roughness level among all the potential actions. S_k^* is the best-achievable level after action k. Reaching S_1^* is still within the agency's control, so if they choose to apply action k, the emissions associated with the difference between S_1^* and S_k^* are included.

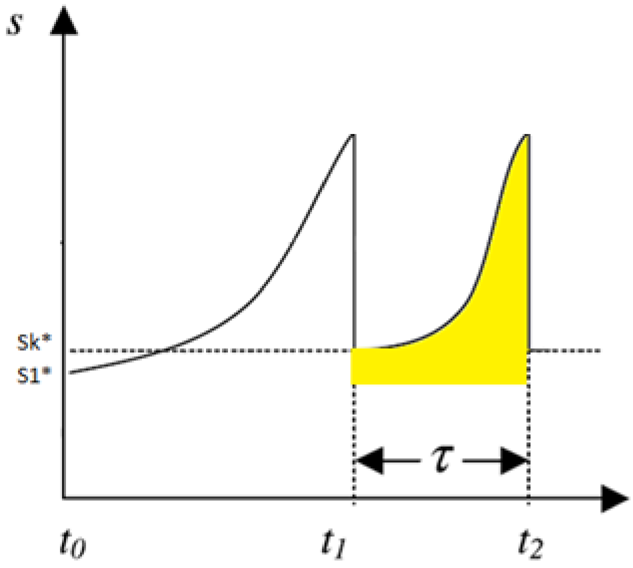

Figure 1: Scope of included user emissions

Solution Methodology

In Reger et al. (2014), we used a similar Lagrangian duality solution methodology to that developed by Sathaye and Madanat (2012). Here we maintain a Lagrangian dual methodology, but solve it in a different manner to allow for the addition of multiple rehabilitation activities. For a given budget at optimality, all facilities in the network will have the same value of Λ (the Lagrange multiplier), so the problem can be treated as separable. We solve for the optimal timing τ of action k on segment j, for all actions k=1,…,K. The optimally timed action which has the lowest value of $D(\Lambda)$ is retained. The budget B is back-calculated by taking the sum of M_{jk} for all j.

$$D(\Lambda) = \max_{\Lambda} \left\{ \inf_{\tau_{jk}} \sum_{j=1}^{J} Q_{jk}\left(\tau_{jk}\right) + \Lambda\left[\sum_{j=1}^{J} M_{jk}\left(\tau_{jk}\right) - B\right] : \tau_{jk} \in (0, \tau_j^e] \ \forall j = 1 \dots J \right\} \quad \text{Eq(4)}$$

$$s.t. \ \ \Lambda \geq 0 \quad \text{Eq(5)}$$

Case Study

The case study focuses on a 1,600 lane-km sample of asphalt pavement segments in California over an infinite time horizon. This 1600 lane-km sample is made up of 311 different segments including both urban and rural roads distributed across Northern California. The traffic data (AADT and AADTT) were obtained from the California Department of Transportation’s (Caltrans) Division of Traffic Operations (Caltrans 2013). Data for rehabilitation actions were obtained from a study of Californian roads, which gives the best-achievable condition and the rate of deterioration after the activity is performed (Tseng 2012). The rehabilitation actions include 5 different thicknesses of overlays (3 cm, 4.5 cm, 7.5 cm, 10.5 cm, 15 cm). Although the only rehabilitation options shown for the case study are different resurfacing thicknesses, the methodology applies to other types of activities, such as seal coating or full-depth reconstruction. It is assumed that 80% of heavy vehicles will travel in the rightmost lane and that deterioration will primarily occur in this lane. Traffic is assumed to stay constant over time. Since rehabilitation is primarily performed overnight in California, the emissions from traffic delay are negligible.

User emissions take into account the additional fuel burned because of the change in fuel consumption due to roughness. The effect of roughness on fuel consumption was determined by Zaabar and Chatti (2015), who found that an additional 1 m/km of IRI increases fuel consumption by 2 to 3% for light vehicles and 1 to 2% for heavy vehicles at highway speeds. We use the midpoints, 2.5% and 1.5% respectively. The gasoline and diesel GHG emissions include emissions from combustion as well as supply chain emissions from extraction, refining, distribution, etc. Agency emissions are calculated using the PaLATE software (PaLATE 2013) and agency costs for resurfacing are taken from (Hand 1999). For agency actions, it is assumed that the agency will not deviate from their schedule if there are adjacent sections being rehabilitated in close timeframes.

Case Study Results

The methodology solves for the optimal action (and corresponding optimal timing) for each segment at each agency budget value. We find that the thinnest resurfacing option (3 cm) is always the optimal action for every 1.6km long segment at every potential budget value. This is a different result than found in the literature, which states that it is always optimal to resurface to the best possible condition if the objective is to minimize total costs (Li and Madanat 2002, Ouyang and Madanat 2006, Gu 2012). For the case study, the best possible condition after resurfacing occurs after applying a 15 cm overlay, while the condition after applying a 3 cm overlay is the worst among the potential options. The result happens to be consistent with the practice of at least one U.S. agency, the Washington State Department of Transportation.

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

The results are shown in Figure 2, with the x-axis representing the agency budget in millions of dollars and the y-axis representing the total GHG emissions in metric tons (mt). As the agency budget increases, total emissions decrease until the emissions-minimizing point is reached. When the budget is low, roads are allowed to deteriorate to poor condition, and the main contribution to emissions comes from the additional fuel consumed by the vehicles. Where budget values are high, the agency is rehabilitating frequently, so the majority of the emissions result from the materials and construction. The slope of the curve is the amount of GHG emissions that could be saved per additional dollar spent by the agency. The results exhibit diminishing returns. For example, an additional \$1M/yr results in a reduction of 100,000 mtCO$_2$e/yr when going from \$1M/yr to \$2M/yr, but only reduces the total emissions by 2,500 mtCO$_2$e/yr when going from \$10M/yr to \$11M/yr. Considering that vehicles emit a majority of the GHG emissions in the transportation sector and the roads which fall under Caltrans' jurisdiction carry over 80% of the VKT in California, scaling up to the entire network would have a significant statewide impact.

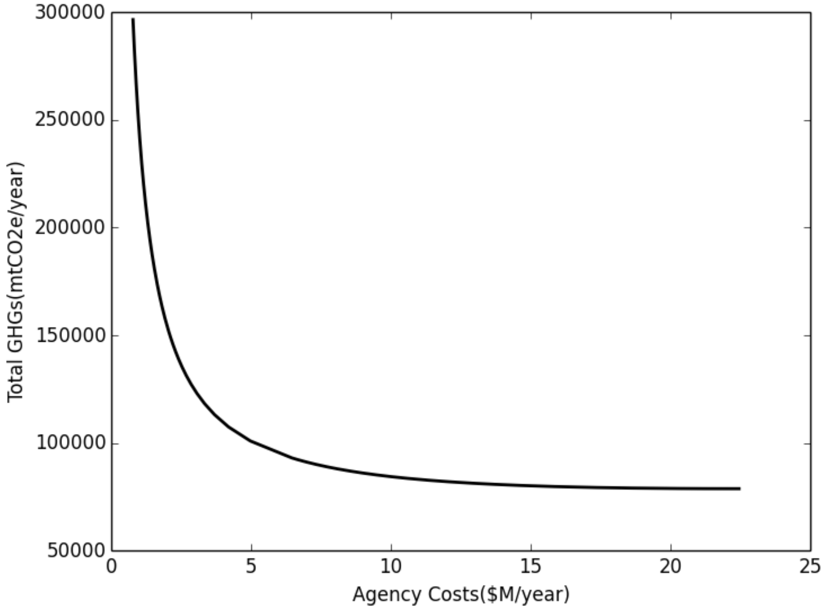

Figure 2: Case study results comparing agency budgets to total GHG emissions

The agency is responsible for optimally using the budget it is allocated, but it does not control the size of that budget. A curve, like the one shown in Figure 2, can help the agency and legislation work together to make budget decisions. Each point on the curve corresponds to a set of optimal actions and action intervals which the agency would apply under a potential budget value. This means that the entity assigning the budget is also choosing the corresponding yearly GHG emissions. The graph gives the agency a way to visualize and quantify the GHG emissions under a given budget as well as determine the potential reductions if additional funds are provided. One way to determine an appropriate budget would be to look at the price of carbon. It is given in the figure by taking the inverse of the slope. For example, if the societal value of carbon was $10/mt, the agency's budget should be $1.3M/yr. Since the cost of carbon changes along the curve, a lower budget would force the agency to operate where the value of carbon was lower than the societal value, while a higher budget would result in spending more than $10/mt for every dollar beyond $1.3M.

Using this methodology, this agency would now have the potential to enter a modified cap-and-trade system. Another entity could purchase carbon credits by supplying the agency with the funds to use for rehabilitation. Standard cap-and-trade systems are typically for a one-time purchase, but what is proposed here is modified such that it could be sold as a contract to a particular entity or resold each year. As an example, if the agency currently has a budget of $5M/yr, each year they would be able to sell 8,000 mtCO$_2$e worth of credits for $1M since that would be the GHG reduction from increasing its budget to $6M/yr.

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

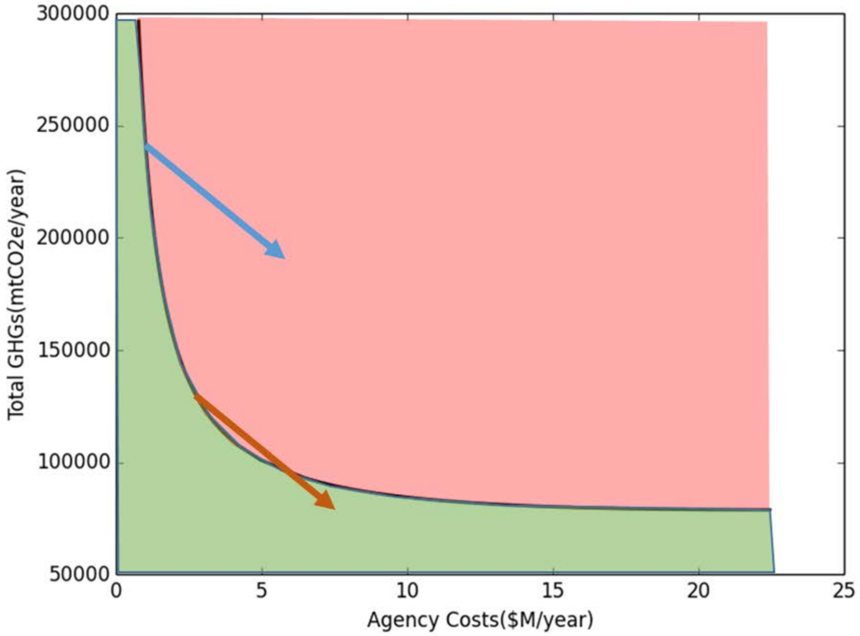

Figure 3: Comparing pavement rehabilitation policy to alternative projects

In addition to GHG emissions, the agency would want to look at the effects of budget values on road condition. Figure 4 shows a "heat map" of the distribution of trigger roughness values for different agency budgets, where a trigger roughness is the level of roughness at which a rehabilitation action will be performed (i.e., the condition of segment j when exactly τ_{jk} years have passed). As the agency budget decreases, the trigger roughness values for the segments increase. At the point where emissions are minimized, there is still a range of optimal trigger roughness values. This confirms the result from Reger et al. (2014), which found that using a universal trigger roughness (i.e., applying the same trigger roughness value to every road in the network) is always suboptimal.

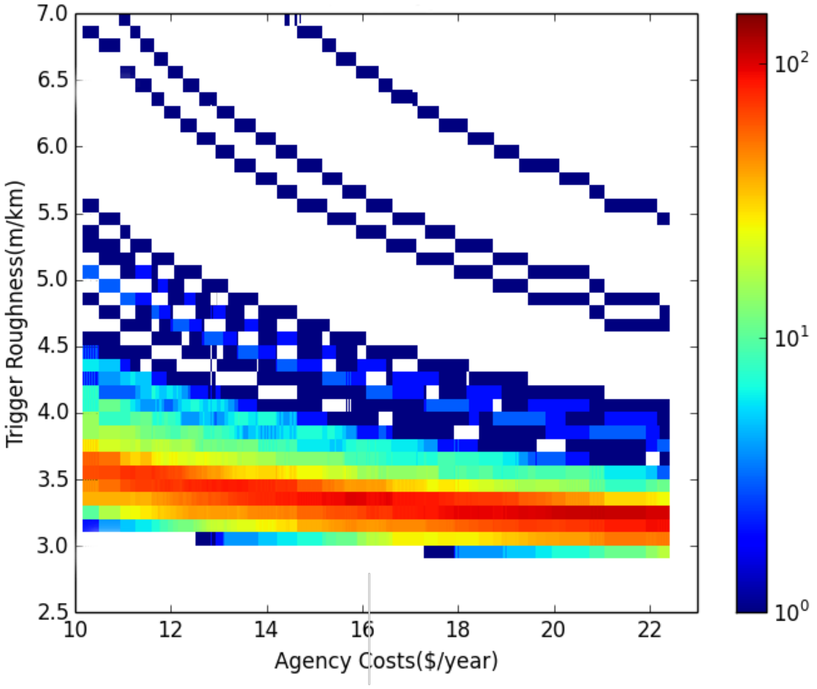

Figure 4: Heat map of the effect of agency budget on pavement condition

In this case study, there are road segments which should be rehabilitated with very little frequency (e.g., $\tau \approx 50$ years). However, the data collected to determine the rate of deterioration did not have a segment which was allowed to deteriorate for 50 years with no intervention. Weathering may prevent these long rehabilitation intervals from being feasible. More data are needed determine how pavements would deteriorate if left without rehabilitation for long time periods and if there are minor treatments which can work as placeholders until it is time for a rehabilitation activity. The issue of condition may also become a factor for these segments since the roughness will surpass what is typically seen on paved roads in rich countries. In this case, the agency may have to allocate some of the budget to these roads sub-optimally, but since only 2% of the case study roads fall into this category, it will not greatly affect the yearly emissions.

Uncertainty and Sensitivity Analysis

The parameters tested for sensitivity analysis were the deterioration rate, best achievable roughness level, and percentage change in fuel consumption. To represent uncertainty with respect to the best achievable roughness level and deterioration rate, we assume that each is normally distributed, with the mean being the value used earlier in the case study and the standard deviation being 25% of the mean value (25% was used such that there was a wide range of deterioration rates while also making sure that there is never a negative value). We then assume that the agency will use a predetermined policy, where they always apply the action and timing specified by the model. This means that if they are supposed to resurface at an interval of 10 years expecting the roughness to be 3.0 m/km, they will still resurface at 10-year intervals for that section even if the pavement condition is 2.0 m/km or 4.0 m/km at that time.

Figure 5 shows the results of the sensitivity analysis. The optimal policies are robust to the deterioration rate and the best achievable roughness level. The black line represents the predicted value of the GHG emissions, with the red lines representing the values of emissions for the simulations. The uncertainty affects the optimal policies when the budgets are high. Figure 6 shows a zoomed-in portion of Figure 5 when the agency budget is between \$15M/yr and \$23M/yr. An agency may not be guaranteed to see the reductions they expect from spending more money in this range. For example, spending an additional \$4M/yr, from \$15M/yr to \$19M/yr, would have an expected reduction of 1,000 mtCO2e/yr, but the emissions from the simulations at \$19M/yr had a range of 9,000 $mtCO_2e$/yr. Therefore, the increased spending may lead to no reductions (or even increases) in GHG emissions.

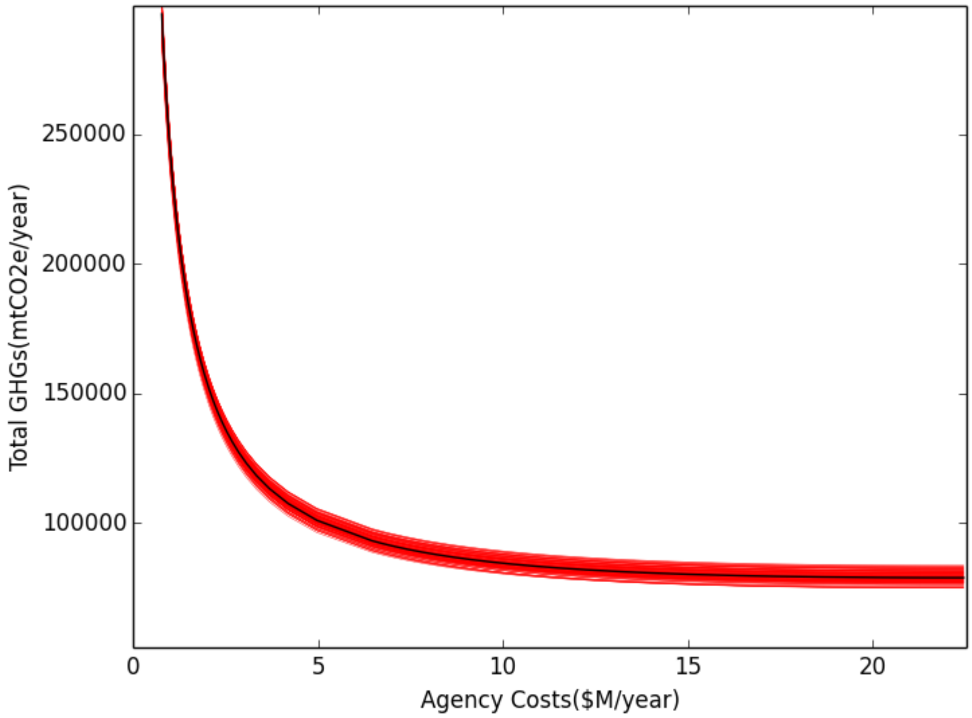

Figure 5: Sensitivity analysis for pavement deterioration rate and best achievable roughness level

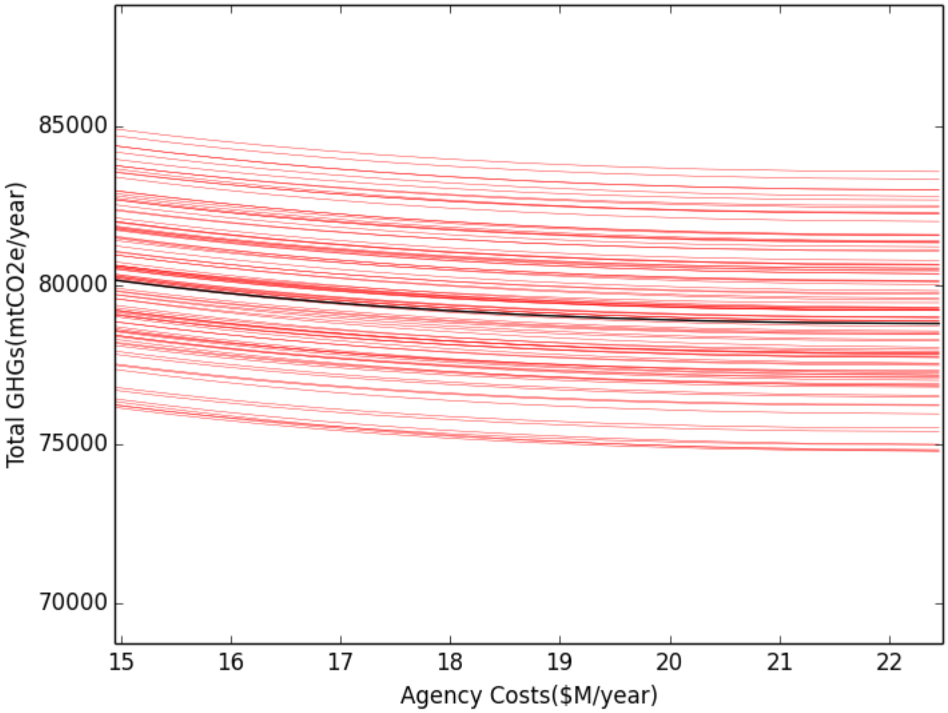

Figure 6: Zoomed-in portion of Figure 5, focusing on where budgets are near the emissions optimizing point

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

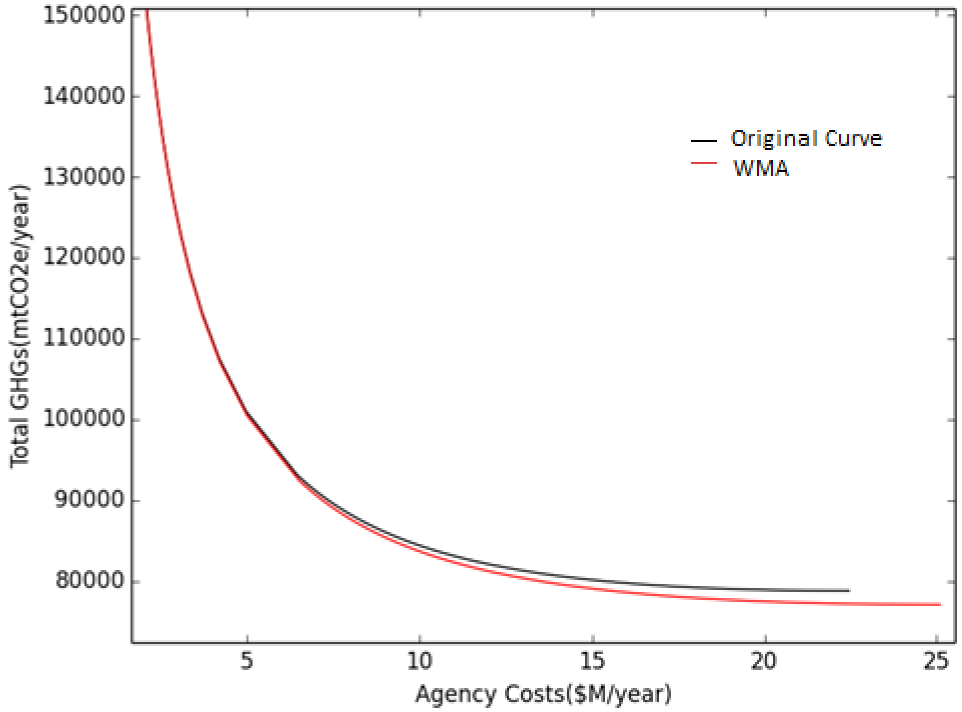

Figure 7: Potential effect of warm-mix asphalt technology on rehabilitation policy

Sensitivity to Changes in Pavement Technology

New pavement technologies, such as warm-mix asphalt (WMA), could affect rehabilitation policy. WMA uses a lower mixing temperature than traditional hot-mix asphalt, and in a best case scenario has the potential to reduce GHG emissions from an asphalt mix by up to 20% (Rodriguez-Alloza 2015). Figure 7 shows the effect of using WMA for rehabilitation on the case results, assuming a 20% reduction in GHG emissions from asphalt and no change in pavement performance or unit price. There is almost no benefit until the agency budget is greater than \$10M/yr. This is because when the budget is low, there are few rehabilitations performed each year, so the user emissions are the main contributors to the total. Near the emissions minimizing point, using WMA can result in savings of up to 3,000 $mtCO_2e$/yr, since there will be a sufficient number of rehabilitations performed each year. However, it is unlikely that an agency will be operating at this point on the curve. Beyond an agency budget of \$10M/yr, the cost of saving an additional metric ton of carbon is upwards of \$700/$mtCO_2e$ which is higher than carbon has ever been traded on the market. There may be other benefits to WMA, such as improved workability and laborer safety, but with respect to GHG reductions in pavement rehabilitation policies, it will provide little benefit unless it brings significant improvements in performance.

The cost of asphalt may change with the recent drop in oil prices. Bitumen is a product of petroleum refining and is also the most expensive part of the asphalt mix. Figure 8 shows the results assuming a 20% reduction in rehabilitation costs. The effect is significant for low budget values, but is less noticeable as the agency budget increases. At a budget of $1M/yr, the 20% reduction in costs would reduce the GHG emissions by 50,000 mtCO2e/yr. When the budget is $15M/yr or higher, the effect is negligible. This occurs because a reduction in costs stretches the budget farther, allowing more roads to receive rehabilitation and overall reducing GHG emissions. It is equivalent to increasing the budget.

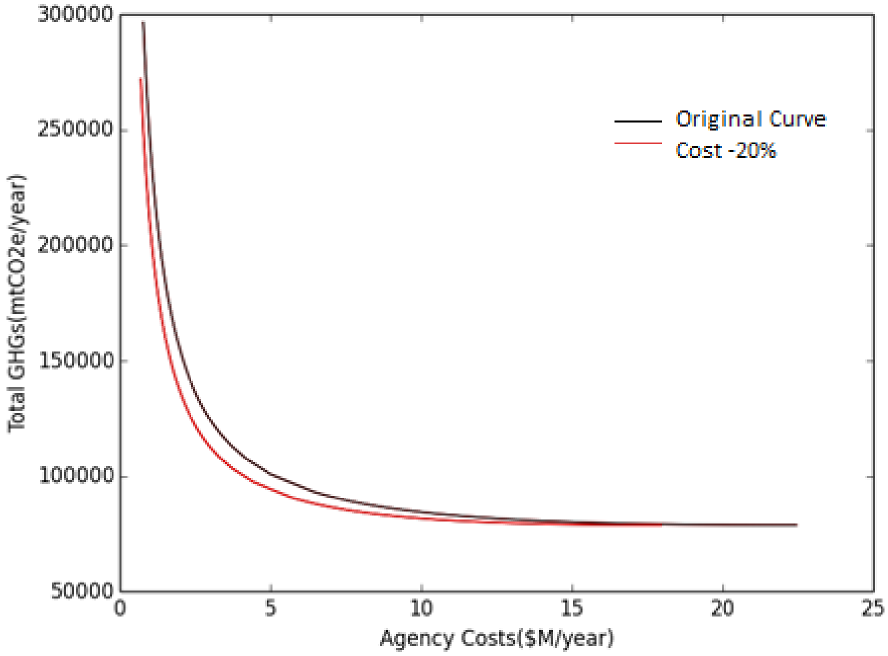

Figure 8: Effect of reducing rehabilitation costs by 20%

Conclusion

This letter presents an approach that can be followed by a road agency to minimize its GHG emissions from rehabilitation while operating under a constrained financial budget. A Lagrangian dual solution methodology is used to efficiently solve for the optimal resurfacing policies in a large-scale network. The results provide the optimal timing along with the optimal actions for every road segment in the network. An agency can use these results to make the case for a higher rehabilitation budget to achieve their emissions reduction target. It is also possible to implement a system where the agency could sell carbon credits by quantifying the emissions reductions from increasing its operating budget and price accordingly. This methodology also allows the agency to compare spending money on pavement rehabilitation or another project within its scope (e.g., roadway lighting) to determine which is a better investment.

A case study of Californian roads was examined and it was found that it is optimal to apply frequent, thin resurfacings, which is contrary to the less frequent, thick overlays specified in the literature for minimizing costs. Sensitivity analyses showed that the solutions are robust with respect to the deterioration rate, best achievable roughness level, and effect of roughness on fuel consumption. The effect of using WMA was determined to only be significant when agency budgets are high since at low budget values rehabilitation is infrequent. However, if asphalt prices fall or the agency finds a way to reduce costs, the potential savings in GHG emissions are significant when the budget is low.

One assumption of this work is that pavements are perpetual. This implies that pavements are designed such that the damage is mainly contained within the surface layer and does not permeate to the underlying layers. While this may be the case in rich countries and for well-constructed roads, it is unlikely to be true in poor countries where money for road building is scarce or for locations with low construction quality. If the pavement is not sufficiently strong, when a resurfacing is performed, the pavement's condition will improve but underlying damages will remain. Therefore, the level of roughness after resurfacing would be higher and the rate of deterioration faster. Future work should include both reconstruction and resurfacing as alternatives so that the methodology is applicable more broadly.

Another extension should be to include other environmental metrics that an agency may be interested in minimizing, such as particulate matter (PM). The effects of PM are local, so it will be necessary to determine the population near roads and asphalt plants. This research assumed that the agency will choose the asphalt plant that is the closest to a construction site, but this may change when including PM. It may be better to use a plant that is farther away from the construction site and also is in a sparsely populated area.

The idea of simultaneous optimization including costs and GHG emissions can be extended to topics beyond pavement management. Within transportation, the idea has been applied to public transportation systems (Griswold et al 2013, Griswold et al 2014). Outside of transportation, researchers have examined tradeoffs with other technologies, such as water distribution systems (Wu 2009) and cogeneration (Bamufleh 2013). We hope that some of the ideas in this paper (e.g., using a Pareto curve to compare alternatives, selling carbon credits, etc.) can find use in the aforementioned topics as well as new areas where these types of tradeoffs have yet to be explored.

Acknowledgments

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References

Air Resources Board (2014). Assembly Bill 32 Overview. *California Environmental Protection Agency,* <http://www.arb.ca.gov/cc/ab32/ab32.htm>. (August 4, 2014)

Bai, Q., Labi, S., & Sinha, K. C. (2011). Trade-off analysis for multiobjective optimization in transportation asset management by generating Pareto frontiers using Extreme Points

Nondominated Sorting Genetic Algorithm II. *Journal of Transportation Engineering*, *138*(6), 798-808.

Bai, Q., Ahmed, A., Li, Z., & Labi, S. (2014). A Hybrid Pareto Frontier Generation Method for Trade-Off Analysis in Transportation Asset Management. *Computer-Aided Civil and Infrastructure Engineering*[SMM1].

Bamufleh, H. S., Ponce-Ortega, J. M., & El-Halwagi, M. M. (2013). Multi-objective optimization of process cogeneration systems with economic, environmental, and social tradeoffs. *Clean Technologies and Environmental Policy*, *15*(1), 185-197.

Bryce, J. M., Flintsch, G., & Hall, R. P. (2014). A multi criteria decision analysis technique for including environmental impacts in sustainable infrastructure management business practices. *Transportation Research Part D: Transport and Environment*, *32*, 435-445.

Caltrans (2014) Traffic Counts. *Caltrans Division of Traffic Operations*, <http://traffic-counts.dot.ca.gov/> (August 26, 2015)

Census Bureau (2014). Highway Mileage by State. *U.S. Census Bureau*, <https://www.census.gov/compendia/statab/2012/tables/12s1089.pdf >. (November 25, 2014)

Chester, M., and Horvath, A. (2009). Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environmental Research Letters*, *4*(2), 024008.

Cicas, G., Hendrickson, C.T., Horvath, A., and Matthews, H.S. (2007). A regional version of a U.S. economic input-output life-cycle assessment model. *International Journal of Life Cycle Assessment*, *12*(6), 365-372.

EPA (2014) Sources of Greenhouse Gas Emissions *United States Environmental Protection Agency* <http://www.epa.gov/climatechange/ghgemissions/sources.html> (March 20, 2015)

Faghih-Imani, A., & Amador-Jimenez, L. (2013). Toward Sustainable Pavement Management: Incorporating Environmental Impacts of Pavement Treatments into a Performance-Based Optimization. *Transportation Research Record: Journal of the Transportation Research Board*, (2366), 13-21.

Federal Highway Administration (2012). Smoothness. *U.S. Department of Transportation*, <http://www.fhwa.dot.gov/Pavement/smoothness/index.cfm>. (March 7, 2013)

Federal Highway Administration (2014). Traffic Volume Trends. *U.S. Department of Transportation*, <http://www.fhwa.dot.gov/policyinformation/travel_monitoring/14novtvt/14novtvt.pdf >. (November 20, 2014)

Fwa, T. F., Chan, W. T., and Hoque, K. Z. (2000). Multiobjective optimization for pavement maintenance programming. *Journal of Transportation Engineering*, *126*(5), 367-374.

Gosse, C. A., Smith, B. L., & Clarens, A. F. (2012). Environmentally preferable pavement management systems. *Journal of Infrastructure Systems*, *19*(3), 315-325.

Griswold, J. B., Madanat, S., & Horvath, A. (2013). Tradeoffs between costs and greenhouse gas emissions in the design of urban transit systems. *Environmental Research Letters*, *8*(4), 044046.

Griswold, J. B., Cheng, H., Madanat, S., & Horvath, A. (2014), Unintended Greenhouse Gas Consequences of Lowering Level of Service in Urban Transit Systems. *Environmental Research Letters*, 9(12), 124001.

Gu, W., Ouyang, Y., and Madanat, S. (2012). Joint optimization of pavement maintenance and resurfacing planning. *Transportation Research Part B: Methodological*, *46*(4), 511-519.

Hand, A. J., Sebaaly, P. E., and Epps, J. A. (1999). Development of performance models based on department of transportation pavement management system data. *Transportation Research Record: Journal of the Transportation Research Board*, *1684*, 215-222.

Horvath, A., and Hendrickson, C. (1998). Comparison of environmental implications of asphalt and steel-reinforced concrete pavements. *Transportation Research Record: Journal of the Transportation Research Board*, *1626*(1), 105-113.

Li, Y., and Madanat, S. (2002). A steady-state solution for the optimal pavement resurfacing problem. *Transportation Research Part A: Policy and Practice*, *36*(6), 525-535.

Li, J., Muench, S. T., Mahoney, J. P., Pierce, L., and Sivaneswaran, N. (2004). Application of HDM-4 in the WSDOT highway system. *University of Washington, Report WA-RD 588.1*. <http://depts.washington.edu/trac/bulkdisk/pdf/588.1.pdf> (March 7, 2013)

Lidicker, J., Sathaye, N., Madanat, S., and Horvath, A. (2013). Pavement resurfacing policy for minimization of life-cycle costs and greenhouse gas emissions. *Journal of Infrastructure Systems*,*19*(2), 129-137.

Ouyang, Y., and Madanat, S. (2006). An analytical solution for the finite-horizon pavement resurfacing planning problem. *Transportation Research Part B: Methodological*, *40*(9), 767-778.

PaLATE (2013). Pavement Life-cycle Assesment Tool for Environmental and Economic Effects. <http://www.ce.berkeley.edu/~horvath/palate.html>. (March 24, 2014)

Paterson, W. D. (1987). *The Highway Design and Maintenance Standard Series-Road Deterioration and Maintenance Effects.* A World Bank Publication, The John Hopkins University Press, Baltimore, Maryland.

Reger, D., Madanat, S., and Horvath, A. (2014). Economically and environmentally informed policy for road resurfacing: tradeoffs between costs and greenhouse gas emissions. *Environmental Research Letters*, *9*(10), 104020.

Revi, A., D.E. Satterthwaite, F. Aragón-Durand, J. Corfee-Morlot, R.B.R. Kiunsi, M. Pelling, D.C. Roberts, and W. Solecki, (2014): Urban areas. In: *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 535-612.

Rodríguez-Alloza, A. M., Malik, A., Lenzen, M., & Gallego, J. (2015). Hybrid input–output life cycle assessment of warm mix asphalt mixtures. *Journal of Cleaner Production*, *90*, 171-182.

Santero, N., Harvey, J., and Horvath A. (2011*a*). Environmental policy for long-life pavements. *Transportation Research Part D: Transport and Environment*, *16*(2), 129-136.

Santero, N. J., and Horvath, A. (2009). Global warming potential of pavements. *Environmental Research Letters*, *4*(3), 034011.

Santero, N., Masanet, E., and Horvath A. (2011*b*). Life-cycle assessment of pavements. Part II: Filling the research gaps. *Resources, Conservation and Recycling*, *55*(9-10), 810-818.

Sathaye, N., and Madanat, S. (2012). A bottom-up optimal pavement resurfacing solution approach for large-scale networks. *Transportation Research Part B: Methodological*, *46*(4), 520-528.

Sathaye, N., Horvath A., and Madanat, S. (2010). Unintended impacts of increased truck loads on pavement supply-chain emissions. *Transportation Research Part A: Policy and Practice*, *44*(1), 1-15.

Sedjo, R. A., and Marland, G. (2003). Inter-trading permanent emissions credits and rented temporary carbon emissions offsets: Some issues and alternatives. *Climate Policy*, *3*(4), 435-444.

Tseng, E. *The Construction of Pavement Performance Models for the California Department of Transportation New Pavement Management System*. M. Sc. Thesis. University of California, Davis, 2012.

Wang, T., Lee, I. S., Kendall, A., Harvey, J., Lee, E. B. E., and Kim, C. (2012). Life cycle energy consumption and GHG emission from pavement rehabilitation with different rolling resistance. *Journal of Cleaner Production*, 33, 86-96.

Wang, T., Harvey, J., and Kendall, A. (2014). Reducing greenhouse gas emissions through strategic management of highway pavement roughness. *Environmental Research Letters*, *9*(3), 034007.

Watanatada, T., Dhareshwar, A.M., and Lima, P.R.S.R. (1987). *Vehicle Speeds and Operating Costs: Models for Road Planning and Management.* A World Bank Publication, The Johns Hopkins University Press, Baltimore, Maryland.

White House (2014) Fact Sheet: U.S.-China Joint Announcement on Climate Change and Clean Energy Cooperation, *Office of the Press Secretary* <https://www.whitehouse.gov/the-press-office/2014/11/11/fact-sheet-us-china-joint-announcement-climate-change-and-clean-energy-c> (Accessed March 26, 2015)

Wu, W., Simpson, A. R., & Maier, H. R. (2009). Accounting for greenhouse gas emissions in multiobjective genetic algorithm optimization of water distribution systems. *Journal of Water Resources Planning and Management*, *136*(2), 146-155.

Zaabar, I., and Chatti, K. (2014). Estimating Vehicle Operating Costs Caused by Pavement Surface Conditions. *Transportation Research Record: Journal of the Transportation Research Board*, *2455*(1), 63-76.

Zhang, H., Keoleian, G. A., Lepech, M. D., and Kendall, A. (2010). Life-cycle optimization of pavement overlay systems. *Journal of Infrastructure Systems*, *16*(4), 310-322.

Zhang, H., Keoleian, G., and Lepech, M. (2013). ”Network-Level Pavement Asset Management System Integrated with Life-Cycle Analysis and Life-Cycle Optimization.” *Journal of Infrastructure Systems*, *19*(1), 99–107.