Economically and environmentally informed policy for road resurfacing: tradeoffs between costs and greenhouse gas emissions

Darren Reger\(^1,4\), Samer Madanat\(^2\) and Arpad Horvath\(^3\)

\(^1\) Department of Civil and Environmental Engineering, University of California, Berkeley, 116 McLaughlin Hall #1720, Berkeley, CA 94720, USA
\(^2\) Department of Civil and Environmental Engineering, University of California, Berkeley, 109 McLaughlin Hall #1720, Berkeley, CA 94720, USA
\(^3\) Department of Civil and Environmental Engineering, University of California, Berkeley, 215 McLaughlin Hall #1720, Berkeley, CA 94720, USA

E-mail: reger@berkeley.edu, madanat@ce.berkeley.edu and horvath@ce.berkeley.edu

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Abstract
As road conditions worsen, users experience an increase in fuel consumption and vehicle wear and tear. This increases the costs incurred by the drivers, and also increases the amount of greenhouse gases (GHGs) that vehicles emit. Pavement condition can be improved through rehabilitation activities (resurfacing) to reduce the effects on users, but these activities also have significant cost and GHG emission impacts. The objective of pavement management is to minimize total societal (user and agency) costs. However, the environmental impacts associated with the cost-minimizing policy are not currently accounted for. We show that there exists a range of potentially optimal decisions, known as the Pareto frontier, in which it is not possible to decrease total emissions without increasing total costs and vice versa. This research explores these tradeoffs for a system of pavement segments. For a case study, a network was created from a subset of California’s highways using available traffic data. It was shown that the current resurfacing strategy used by the state’s transportation agency, Caltrans, does not fall on the Pareto frontier, meaning that significant savings in both total costs and total emissions can be achieved by switching to one of the optimal policies. The methods presented in this paper also allow the decision maker to evaluate the impact of other policies, such as reduced vehicle kilometers traveled or better construction standards.

Keywords: transportation, optimization, pavement, asphalt, Pareto, LCCA, GHG emissions

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1. Introduction
Climate change is becoming an important subject of discussion and action globally. Many countries and industries are devising plans and steps to adapt to and mitigate the effects of climate change. California has been active in discussing climate change mitigation policy since the passing of Assembly Bill 32 in 2006, the state law that set greenhouse gas (GHG)
emission reduction goals (Air Resources Board 2014). One of the specific aspects mentioned is the need for cleaner transportation. The California Department of Transportation (Caltrans) is in charge of a system consisting of over 80,000 lane-kilometers of roads, traversed by vehicles driving 2.7 billion kilometers per year (Caltrans 2011). The potential reductions in emissions with the right strategies are significant (see, e.g., Sathaye et al 2010, Santero et al 2011, 2011a, 2011b). Caltrans has investigated several strategies for decreasing the emissions in their scope, such as alternative technologies for manufacturing asphalt for roadways, LED lighting of roads, and use of renewable energy in facility operations. However, additional, yet unexplored opportunities remain (e.g., material selection (Horvath and Hendrickson 1998), local or regional supply chains (Cicas et al 2007)).

Pavement management systems seek only to minimize life-cycle costs that a road agency and users incur. Environmental impacts stemming from emissions, e.g., of GHGs, traditionally have not been taken into account. This paper describes an optimization model we have created to help decision makers adopt pavement resurfacing policies that minimize both total costs and GHG emissions for a road network. The range of potentially optimal decisions is found along the so-called Pareto frontier. Such optimal policies could be adopted by Caltrans or other decision makers in charge of road systems worldwide and can be adapted to include other potential actions such as reduced vehicle kilometers traveled (VKT) to examine their effects on optimal resurfacing policies.

2. Literature review

2.1. Pavement roughness and effects

The global warming potential associated with pavements was examined by Santero and Horvath (2009), who determined that the rolling resistance stemming from pavement roughness had the potential to have the highest impact of all components in the pavement life cycle. Therefore, roughness is the characteristic that is used in this paper as a measure of road condition. Roughness is a measure of how uneven the longitudinal profile is in the wheelpath; it is inclusive of the distresses seen in pavements such as cracking, rutting and potholes (Paterson 1987). The standard measure for roughness is the International Roughness Index (IRI) which is typically measured in m/km or in m/ft, where an IRI of 0.6 m/km corresponds to a perfectly flat road surface. It has been shown to affect fuel consumption as well as vehicle wear and tear (Watanatada et al 1987, Barnes and Langworthy 2004). To keep roads in good condition, agencies can perform a rehabilitation action such as a resurfacing, however, this activity also comes with substantial costs and GHG emissions. The measured value of roughness at which the agency decides to perform an action is known as the trigger roughness.

Roughness also affects users’ perception of ride quality. Beyond a certain threshold, drivers and passengers begin to feel uncomfortable. This threshold was set at 2.7 m/km by the United States Federal Highway Administration (2012), and is supported by an empirical analysis by Shafizadeh and Mannering (2003). Caltrans has recently adopted this same value as its trigger roughness. Another commonly used value is 3.5 m/km, which was used by Caltrans in the past and is currently used by the Highway Design and Maintenance Standards Model (HDM) application for developing countries (Li et al 2004, Lu et al 2009). Since the value of 2.7 m/km is based upon perceived comfort, it may not be optimal in terms of economic or environmental costs; this reasoning is why some agencies may use a different value and why different values are examined in this study.

2.2. Optimization methods for maintenance and rehabilitation

There are three formulations that can be used to optimize pavement maintenance and rehabilitation (M&R); (1) discrete time and discrete state (e.g., Madanat 1993), (2) discrete time and continuous state (e.g., Durango-Cohen 2007), (3) continuous time and continuous state (e.g., Tsunokawa and Schofer 1994). These categories can be further broken up into single or multiple facilities (segments of roadways). The M&R optimization of multiple facilities can be performed by using top-down (e.g., Golabi et al 1982) or bottom-up (e.g., Sathaye and Madanat 2012) approaches. This research utilizes a continuous time and continuous state formulation for multiple facilities, which is preferred because pavement roughness is a continuous variable. The bottom-up approach is chosen because it preserves individual facility characteristics and provides better information for allocating the budget amongst the system of facilities as compared to the top-down approach which only specifies a percentage of facilities which should receive treatment and still requires the final decisions to be made by pavement engineers.

Li and Madanat (2002) solved the problem of optimal pavement resurfacing frequency for an infinite planning horizon using a steady-state solution method. The optimal policy was found to have a threshold structure, where the pavement should always be resurfaced to its best achievable roughness level. This result confirmed earlier empirical work (Darter et al 1985, Camahan 1988) and was confirmed by later theoretical work (Ouyang and Madanat 2006, Gu et al 2012). Sathaye and Madanat (2011, 2012) extended the work by Li and Madanat to solve for a large-scale heterogeneous system of facilities.

There are also methods that focus on optimizing pavement rehabilitation with respect to criteria consisting of more than total costs. Lidicker et al (2013) used a multi-criteria optimization in which GHG emissions and costs were considered for a single facility, and found that there was a tradeoff between costs and GHG emissions resulting in a Pareto frontier with each point representing a potentially optimal pavement rehabilitation strategy for that facility. Zhang et al (2010, 2010a) addressed multi-criteria optimization as well for emissions, energy and costs with respect to the Michigan
highway system, but the focus was on a comparison of a new material, engineered cementitious composites with asphalt and concrete pavements. Zhang et al (2013) used life-cycle optimization in order to determine an optimal strategy while taking sustainability factors into account, but did not examine the tradeoffs between the costs and these factors or delve into policy implications. Wang et al (2012) came up with an LCA model to evaluate energy and GHG emissions for different rehabilitation strategies, and looked at the payback period for agency emissions to be offset by the savings in user emissions, but did not examine costs.

2.3. Problem formulation

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

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

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

\[
\min_j \sum_{j=1}^J \{ V_j(\tau_j) \} \\
= \sum_{j=1}^J \left[ U_j(\tau_j) + M_j(\tau_j) \right] \left( \frac{e^r - 1}{1 - e^{-r\tau_j}} \right) \tag{1}
\]

\[
s.t. \sum_{j=1}^J \{ Q_j(\tau_j) \} \\
= \sum_{j=1}^J \left[ W_j(\tau_j) + A_j(\tau_j) \right] \left( \frac{1}{\tau_j} \right) \leq B, \tag{2}
\]

\[
\tau_j \in [\tau_j^l, \tau_j^u]. \tag{3}
\]

The models that are used in the optimization are presented in detail in the supplementary material in appendix A, available at stacks.iop.org/ERL/9/104020/mmedia.

2.4. Solution methodology

This section presents the solution methods which are used to solve the formulation given in the previous section. The formulation is similar to that of (Sathaye and Madanat 2012), with the exception of changing the constraint and decision variable. The Lagrangian dual formulation of the problem is taken here as it is simple to solve since there is only one dual variable. Additionally, the value for the shadow price directly gives the value for the tradeoff between marginal costs and GHG emissions. Using this, the policy maker can find out where their organization is operating on the Pareto frontier and deduce how much it would cost per metric ton (mt) to reduce their CO$_2$e emissions (where CO$_2$e is carbon dioxide equivalent emissions expressing all GHGs in terms of CO$_2$). The dual formulation utilizes a common nonlinear programming technique and is given in equation (4) with the constraint given in equation (5). $A$ is the Lagrange multiplier, also commonly referred to as the shadow price. Specifics can be found in the supplementary material in appendix B.

\[
D(\Lambda) = \max_\Lambda \left\{ \inf_\tau \sum_{j=1}^J V_j(\tau) \right. \\
+ A \left[ \sum_{j=1}^J Q_j(\tau) - B \right] \\
\left. \tau_j \in [\tau_j^l, \tau_j^u] \forall j = 1 ... J \right\} \tag{4}
\]

\[
s.t. \ \Lambda \geq 0. \tag{5}
\]

2.5. Case study

A sample of flexible pavement segments (defined as 1 km long stretches) from a subset of Californian highways (representing approximately 1600 lane-km or 3% of the state’s entire network) is used to illustrate the benefits of the proposed methodology. The data came from Caltrans’ district 4 (one of the 12 districts in the state), which was chosen because it has a variety of pavement segments which include
highways that run through major urban areas such as San Francisco and Oakland as well as some rural roads which see little traffic. The assumptions and values for the parameters used in the models discussed in the problem formulation are described in the following sections.

2.6. Assumptions

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

2.7. Traffic and pavement

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

2.8. User costs and emissions

User costs considered are a combination of additional fuel consumption and additional wear and tear on vehicles caused by roughness. Zaabar and Chatti (2010) calibrated the HDM-4 model to match conditions seen in the United States and investigated an array of vehicle types at highway speeds. The study found that the change in fuel consumption was linear with respect to roughness with each additional unit of roughness (1 m km$^{-1}$), resulting in an increase of 1.05% in fuel consumption for cars and a 0.725% increase in fuel consumption for trucks. The current average fuel prices of diesel and gasoline in the case study area were used. For vehicle wear and tear, additional costs per km due to one unit of roughness were taken from (Barnes and Langworthy 2004). The GHG emissions associated with the additional burning of fuel as there is no empirical evidence of the additional emissions from tire wear, maintenance, or parts replacement for US conditions. The emissions inventory of fuels (diesel and gasoline) accounted for the entire supply chain (resource extraction, refining, distribution). The total user costs and emissions for each segment are weighted by the amount of traffic. Caltrans performs its maintenance activities at night when there is little traffic, so user delay is not included in the cost or emissions functions.

2.9. Agency costs and emissions

State agencies typically set overlay thicknesses, which they apply under given circumstances. For example, Caltrans typically applies a 0.075 m (0.25 ft) hot mix asphalt overlay when the roughness level is greater than 2.7 m km$^{-1}$ (Caltrans 2012). Due to this method of application, overlay costs are typically given in dollars per distance. As this paper investigates various overlay thicknesses, resurfacing costs need to be determined in a different manner. Hand et al (1999) obtained costs from the New Jersey Department of Transportation Operations Division, which included engineering and construction costs for various resurfacing thicknesses ranging from 0.05 to 0.125 m, and found that costs are linear with thickness. To address agency GHG emissions from resurfacing, the PaLATE software was used (PaLATE 2013).

2.10. Case study results

The results for the network-level analysis are shown in figure 1. Before delving into the benefits of the optimization, the effect of the recent policy change by Caltrans from a trigger roughness of 2.7 m km$^{-1}$ was considered. We estimated that the new resurfacing policy saves 3600 metric tons CO$_2$ yr$^{-1}$ and $0.6$ million yr$^{-1}$ in total costs. This corresponds to an emissions reduction of 14% and a cost reduction of 2.5%. While it is shown that the new policy is a step towards bringing the system closer to optimality, there is still room for improvement. Emissions could be reduced by another 540 mt CO$_2$ (2.5%) and costs by another $0.3$ million (1.5%) if the agency were to move from the 2.7 m km$^{-1}$

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Results comparing the Pareto frontier to the current and past practices applied by Caltrans. (CRP: Caltrans recent policy (trigger roughness of 2.7 m km$^{-1}$), CPP: Caltrans past policy (trigger roughness of 3.5 m km$^{-1}$)).}
\end{figure}
policy to the cost-minimizing point on the Pareto frontier, which is the point obtained when total costs are minimized without an emissions constraint. Each point on the Pareto frontier corresponds to a potentially optimal policy consisting of trigger roughness values for each facility. For example, a point close to the cost optimal would have trigger roughness values between the cost- and emissions-optimal values, but more closely resembling the cost optimal. This new approach can be easily adopted into practice since it retains the threshold-based decision-making process currently used by pavement engineers, with the only difference being the need to specify different optimal thresholds for each segment. If an agency is given an emissions budget, it can then determine if that budget is feasible and what the total costs would be in the network with that constraint. To illustrate what happens at a facility level in the network under the proposed optimization, several single facility cases are examined in the supplementary material in appendix D.

2.11. Relationship to carbon price

The slope of the Pareto frontier represents the price of CO\textsubscript{2} at that point. Two possible prices for CO\textsubscript{2} are considered (figure 2): the price of $13.62/mt CO\textsubscript{2}e, determined from California’s second carbon auction (Environmental Leader 2013), and the price of $110/mt CO\textsubscript{2}e, from a study (Knittel and Sandler 2011). It is possible to make some conclusions about the amount of CO\textsubscript{2}e that can be saved by moving from the cost-optimal point to either of those two points. For the California price, although it is very close to the cost optimal point, it would still result in a savings of 50 mt CO\textsubscript{2}e yr\textsuperscript{-1} (0.2%). The value from (Knittel and Sandler 2011) would result in a savings of 450 mt CO\textsubscript{2}e yr\textsuperscript{-1} (2%) since it is located farther from the cost-optimal point on the graph. The savings discussed are only for the subset of Caltrans district 4 roads used in the case study. Scaling up to the entire Caltrans network will lead to higher savings as the case study only accounts for about 3% of the entire network. Looking at carbon price another way, the given emissions budget decides the societal value for carbon. For example, if Caltrans was told they had to reduce their GHG emissions to 20 000 mt CO\textsubscript{2}e yr\textsuperscript{-1} for the subset of roads discussed in the case study, this would correspond to a CO\textsubscript{2} value of approximately $750/mt, which is considerably higher than carbon has ever been valued on the market. This can lead to more informed emissions budgeting. Another extension of the carbon pricing is that it can be used to compare it to the costs of carbon reductions from alternative actions (such as using LEDs in roadway lighting).

2.12. User versus agency costs

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

2.13. VKT reduction (policy sensitivity analysis)

There are some cases in which the agency cannot meet its emissions target from simply moving along the Pareto frontier, regardless of the budget. They would need to consider other policies, such as reducing total VKT. Such action reduces both total emissions and total costs for the network, as shown in figure 4. A 10% reduction in VKT reduces the yearly costs by about $0.6 million (2.5%) and yearly...
emissions by 950 mt CO₂ yr⁻¹ (4.5%). A 20% reduction sees costs reduced by $1.3 million yr⁻¹ (5%) and emissions by 1900 mt CO₂ yr⁻¹ (9%). User costs are expected to drop since there will be fewer travelers on the roads, but agency costs also see a reduction of $0.2 million for 10% VKT reduction and $0.4 million for a 20% VKT drop since the roads need to be resurfaced less frequently. In the situation where roads are under-designed, a reduction in VKT will be even more significant since it will also slow the deterioration due to reduced truck traffic. Other potential policies, such as improved construction standards, are discussed in the supplementary material in appendix E.

3. Conclusion

This paper presents a framework for including GHG emissions minimization into pavement resurfacing policy. A realistic deterioration model is used and a case study is performed on a subset of California highways. The recent resurfacing policy change in California (going from a trigger roughness of 3.5 to 2.7 m km⁻¹) was shown to be beneficial for reducing both total costs and total emissions. Although an improvement over the past policy was shown, the recently adopted policy was still found to be sub-optimal. Further reductions in total costs and total emissions can be achieved by switching to a policy that is located on the Pareto frontier which would keep the same threshold-based decision making process, but specify a different optimal trigger roughness value for each segment. It was demonstrated how the societal value of carbon can be used to decide which resurfacing policy to use. The link between an agency being given an emissions budget and how that budget implicitly decides the societal value of carbon was also discussed. Lastly, how agencies can use this optimization method to evaluate their budget needs was also shown.

A useful addition would be to include under-designed roads, since they will deteriorate much more quickly. In this research, roads were assumed to have been designed to meet the traffic that they carry today, but in real-world applications this may not be the case. With pavement lifespans (before reconstruction) lasting over 20 yr, the traffic that they were designed for may differ greatly from what is currently being seen. Future research should either seek to include measured values for structural number, or try to determine which areas experienced the highest traffic growth in the past few years.

Even though the analyzed case focuses on California, the optimization model is applicable to other locations. It was shown that a universal trigger roughness is not optimal, which is a policy used by many countries. For agencies which already use a cost-optimizing pavement management system, this paper shows how they can incorporate GHG emissions into their accounting. Furthermore, the framework allows for the inclusion of additional policies, such as reduced VKT.

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References

Air Resources Board 2014 Assembly Bill 32 Overview. California Environmental Protection Agency (www.arb.ca.gov/c.c./ab32/ab32.htm) (4 August 2014)
Au T and Au T P 1992 Engineering Economics for Capital Investment Analysis (Englewood Cliffs, NJ: Prentice-Hall)
Barnes G and Langworthy P 2004 Per mile costs of operating automobiles and trucks Transp. Res. Rec.: J. Transp. Res. Board 1864 71–7
Caltrans 2011 State of the Pavement 2011 Report California Department of Transportation, Division of Maintenance (www.dot.ca.gov/hq/maint/Pavment/Pavment_Program/PDF/2011_SOP.pdf) (26 April 2013)
Caltrans 2012 California Highway Design Manual California Department of Transportation, Publication Distribution Unit, chapter 630 (www.dot.ca.gov/hq/oppd/hdm/pdf/english/chp0630.pdf) (7 March 2013)
Carnahan J V 1988 Analytical framework for optimizing pavement maintenance J. Transp. Eng. 114 307–22
Cicas G, Hendrickson C T, Horvath A and Matthews H S 2007 A regional version of a US economic input-output life-cycle assessment model Int. J. Life Cycle Assess. 12 365–72
Darter M J, Smith R E and Shahin M Y 1985 Use of life-cycle costing analysis as a basis for determining the cost-effectiveness of maintenance and rehabilitation treatments for developing a network level assignment procedure Proc. North American Pavement Management Conf. (Toronto, Canada)
Durango-Cohen P L 2007 A time series analysis framework for transportation infrastructure management Transp. Res. B 41 493–505
Environmental Leader 2013 California Carbon Price Surpasses Expectations (www.environmentalleader.com/2013/02/25/california-carbon-price-surpasses-expectations/) (20 December 2013)
Federal Highway Administration 2012 Smoothness. US Department of Transportation, (www.dot.ca.gov/hq/oppd/hdm/pdf/english/chp0630.pdf) (7 March 2013)
Golabi K, Kulkarni R B and Way G B 1982 A statewide pavement management system Interfaces 12 5–21
Gu W, Ouyang Y and Madanat S 2012 Joint optimization of pavement maintenance and resurfacing planning Transp. Res. B 46 511–9
Hand A J, Sebaaly P E and Epps J A 1999 Development of performance models based on department of transportation pavement management system data Transp. Res. Rec.: J. Transp. Res. Board 1684 215–22
Horvath A and Hendrickson C 1998 Comparison of environmental implications of asphalt and steel-reinforced concrete pavements Transp. Res. Rec. 1626 105–13
Knittel C R and Sandler R 2011 Cleaning the Bathwater with the Baby: the Health Co-Benefits of Carbon Pricing in Transportation (No. w17390) (Cambridge, MA: National Bureau of Economic Research)
Li J, Muench S T, Mahoney J P, Pierce L and Sivaneswaran N 2004 Application of HDM-4 in the WSDOT highway system Report WA-RD University of Washington(http://depts.washington.edu/trac/bulkdisk/pdf/5881.pdf) (7 March 2013)
Li Y and Madanat S 2002 A steady-state solution for the optimal pavement resurfacing problem Transp. Res. A 36 525–35
Sathaye N and Madanat S 2012 A bottom-up optimal pavement resurfacing solution approach for large-scale networks Transp. Res. B 46 520–8

Sedjo R A and Marland G 2003 Inter-trading permanent emissions credits and rented temporary carbon emissions offsets: some issues and alternatives Clim. Policy 3 435–44

Shafizadeh K and Mannering F 2003 Acceptability of pavement roughness on urban highways by driving public Transp. Res. Rec.: J. Transp. Res. Board 1860 187–93

Tsunokawa K and Schofer J L 1994 Trend curve optimal control model for highway pavement maintenance: case study and evaluation Transp. Res. A 28 151–66

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 J. Cleaner Prod. 33 86–96

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

Zaabar I and Chatti K 2010 Calibration of HDM-4 models for estimating the effect of pavement roughness on fuel consumption for US conditions Transp. Res. Rec.: J. Transp. Res. Board 2155 105–16

Zhang H, Keoleian G A, Lepech M D and Kendall A 2010 Life-cycle optimization of pavement overlay systems J. Infrastruct. Syst. 16 310–22

Zhang H, Keoleian G and Lepech M 2013 Network-level pavement asset management system integrated with life-cycle analysis and life-cycle optimization J. Infrastruct. Syst. 19 99–107

Zhang H, Lepech M D, Keoleian G A, Qian S and Li V C 2010a Dynamic life-cycle modeling of pavement overlay systems: Capturing the impacts of users, construction, and roadway deterioration J. Infrastruct. Syst. 16 299–309