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A Quantitative Analysis of Sustainability and Green Transportation Initiatives in Highway Design and Maintenance

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Abstract

Sustainability and green transportation initiatives have been widely promoted in highway design and maintenance in recent years. While there are many definitions of sustainability and green transportation, there has mainly been a qualitative description of such initiatives in previous works. In this paper we propose a quantitative analysis of sustainability and green transportation from highway design and maintenance perspective. There is a considerable interaction between highway design and maintenance. For example, a well designed and maintained highway should jointly minimize the initial and life-cycle costs. But, generally a precise account of maintenance life-cycle cost analysis is not performed in the design stages of a highway. In this paper a highway alignment optimization problem is analyzed and evaluated based on the joint minimization of initial and life-cycle costs. An illustrative example is presented

Keywords: highway deign; sustainability; highway maintenance; green transportation.

1. Introduction

Sustainable development has been defined by United Nation's Brundtland commission as meeting the needs of the present people while not jeopardizing the needs of the future generation. The definition suggests that the successful application of the principles of sustainable development means setting goals, implementing practices and measuring results which balance the three-legged stool of sustainable development - economy, environment and the social quality of life (Zeitsman 2011). Sustainability in transportation generally refers to transportation that contributes to the sustainable development of the community that owns and uses the system. Traditionally, the development of transportation infrastructure were based on guidelines that minimized the initial cost,

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emphasized traffic mobility with minimal consideration for the social and environmental needs. Global concerns about climate change, environmental impacts and limited financial resources is necessitating the need for a different approach in selecting transportation solutions. Consequently, there is a growing desire for environmental sustainability of transportation infrastructure throughout its life cycle. A sustainable transportation system is safe, healthy, affordable, and renewable, operates fairly, and limits emissions and the use of new and nonrenewable resources (Tighe and Gransberg 2011).

Compliance with federal government's environmental requirement has made it mandatory that environmental consideration must be included in all highway designs. All projects must have National Environmental Policy Act (NEPA)/Environmental approvals unless it can be demonstrated that no permit is required. At operation stages hybrid or alternative fuel vehicles are replacing old fleets to enhance the reduction of Greenhouse gases (GHG). While these measures go a long way in introducing sustainability and green transportation in the transportation infrastructure development process, the concept is yet to be fully implemented at the design and maintenance stages as it is usually very difficult to quantitatively analyze sustainability and green transportation initiatives.

The objective of this study is to provide a quantitative framework for analyzing sustainability and green transportation initiatives in highway design and maintenance. Specifically, we formulate the life-cycle maintenance cost of a highway to be considered in conjunction with various initial costs (such as right-of-way, pavement, and earthwork costs) in the highway alignment optimization process.

2. Literature review

A review of relevant literature is presented here to gain insight to sustainability and green transportation in highway design and maintenance. Maryland State Highway Administration, in collaboration with researchers from the University of Maryland has developed a Model of Sustainability and Integrated Corridors (MOSAIC), to measure the sustainability of highway improvement options. The sustainability indicators identified for the model are geared to planning stages of highway development, but the quantitative description of the model's input and output is a significant improvement from the previous treatment of sustainability which focused on qualitative descriptions. This is a tool which can be used to identify environmental mitigation needs early in the planning process. The robustness of the model has been tested in a case study (US 15 Corridor, Frederick Maryland, USA) when two proposed improvements were compared with the base condition. MOSAIC yielded numerical and graphical output needed for decision making (Zhang et al. 2011).

SHARP2 Report S2 (2012) developed an integrated ecological framework to support transportation planning while enhancing timely project delivery. It has updated wetland maps, and created inductive models to predict locations where sensitive species are most likely to be located and where they are unlikely to occur. The framework also has an environmental accounting and crediting method that can be used to assess alternative processes. The aim of this tool is to have both transportation agencies and the regulatory agencies on one page to expedite the project delivery.

NCHRP Report 708 (2011) provides a flexible framework through which transportation agencies can apply the concepts of sustainability through performance measures to evaluate programs and gauge the effectiveness of these strategies in implementing sustainability. It provides practical examples of sustainability measurements from various agencies.

Maji and Jha (2011) developed a model to quantify sustainability in highway design by incorporating the cost of environmentally preserved land into the highway alignment cost. AASHTO (2009) defines sustainability and sustainable transportation as a two-stage process of highway design. It also describes the role of Departments of Transportations in sustainability. The main focus is a list outlining the brief description of transportation sustainability best practices for planning, design, construction, operation, maintenance, and a final performance measure.

Bevan (2009) defines sustainability and identifies a way of applying sustainable design guidelines for enhancing urban streets. He describes applicable sustainable solution to urban streets showing various examples. Guidelines for assessing sustainable urban street design options and key challenges expected when the principles are adopted are also discussed.

Maryland State Highway Administration Business Plan has six key performance areas (KPA). In each area there are performance measures used to determine if the goals are being met or not. Performance measure data from two KPAs, System Preservation & Maintenance and Environmental Compliance & Stewardship may be used for quantitative analysis of sustainability and green transportation.

McVoy (2008) describes the evolution of New York State Department of Transportation's GreenLITES program from initially being a tool for assessing Capital project environmental sustainability to a collection of tools (rating system, spreadsheets, etc.) for assessing projects, plans, operation, maintenance and regional programs. GreenLITES project design tool identifies several sustainable items in five categories. The design tool has alignment selection as one of the categories. Additionally, The GreenLITES operation tool can be used to plan and report broad range of environmental/sustainability activities related to bridge, road maintenance, and facility management.

Eisenman (2012) proposed a strategy for Georgia Department of Transportation to enable the agency to compare projects based on sustainability goals and outcomes. He explores the existing transportation sustainability initiatives or programs from federal government, programs of academic origin, programs from consultants and professional organizations and programs from state and local departments of transportation. Further, he has used the New York State's GreenLITES program as a template and starting point for the development of a rating system for Georgia Department of Transportation. The rating is based on score cards which allow numerical values to be assigned for specific sustainability and green initiative or practice.

Muench (2009) describes Greenroads, a performance metric for quantifying sustainable practices associated with roadway design and construction. Greenroads assigns seven key components to sustainability and defines a sustainable road project as one that incorporates the seven components into the design and construction process. Some sustainability best practices used by Greenroads such as NEPA compliance, noise mitigation, and pavement maintenance are mainstream practices in highway design and maintenance.

INVEST (Infrastructure Voluntary Evaluation Sustainability Tool) is a practical, web-based, collection of voluntary best practices, designed to help transportation agencies integrate sustainability into their policies, processes , procedures, practices, and projects. The use is voluntary for all transportation and planning agencies.

3. Sustainability and green transportation in highway design and maintenance

The above literature review shows that the bulk of implementation of sustainability and green transportation initiatives are in the form of system rating and performance measures programs. (SHARP 2, 2012; Zhang et. al, 2011; Zietsman, 2011; Muench, 2009; McVoy, 2008; Eisenman, 2012). The system ratings are used in most cases to select the best solution alternative during planning stages and performance measures are used to rate construction processes. However, sustainability and green transportation initiatives are yet to be fully integrated into the mainstream highway design and maintenance. Construction ratings systems or performance measures do have scoring practices which can be considered as part of design. AASHTO (2009) and Bevan (2007) have highlighted best practices which are strictly design issues. While GreenLITES program (McVoy, 2008) has in the project design tools a category of sustainability indicator dealing with highway alignment selection. Eisenman (2012) has adopted GreenLITES as its starting point and is therefore having a category scoring selection of highway alignment modified to meet Georgia Department of transportation's requirements.

As noted earlier, most implementation of sustainability and green transportation initiatives are in the form of system ratings and performance measures, and are focused in planning and construction stages of project development. Bryce (2008) observes that current sustainability and green initiatives are focused on efficient cars and short term cost of building roads. He suggests that long-term cost reductions through more sustainable highway design, construction and maintenance, such as advance planning, intelligent construction and efficient maintenance techniques should be the main focus of federal, state and local DOTs. Eisenman's (2008) summary of attributes considered by major rating systems include runoff quantity, noise, materials, water quality, and aquatic habitat; issues normally encountered in highway design. For example, runoff quantity features vary prominently in storm water management design, and erosion and sediment control design. Maryland State Highway Administration is currently implementing the following as sustainability and green highway design initiatives:

- Design road alignments to avoid wetlands and parks
- Provide landscape trees and flowering plants to prevent erosion
- Provide wider span on bridges to lessen construction work in waterways
- Provide truck and bus lanes on long upgrades to remove slower vehicles out of the way

And as sustainability and green highway maintenance initiatives:

- Constantly monitor signal operations to provide optimum time for the heaviest traffic movement
- Use de icers that are not chemically toxic to streams and waterways.

AASHTO (2009) has described best sustainability practices under design/construction and operation/maintenances categories such as use of porous asphalt which improves safety and is beneficial to the environment and use of adaptive traffic control system responding to traffic patterns in real-time. Muench (2009) and Bevan (2009) also provide additional best practices.

Maji and Jha (2011) developed a model to simultaneously minimize highway alignment cost and the impacted area of environmentally preserved land. The alignment cost was assumed to consist of right-of-way, construction cost, earthwork, vehicle operation cost, and user cost. However, the proposition of sustainability in the listed costs was not specified. If the Maji and Jha's model is used as a starting point, incorporating the best design practices highlighted in Eisenman (2012), AASHTO (2009); Bevan (2008), and Zhang (2011) would produce a more robust model capturing additional highway design and maintenance features of sustainability.

For better decision making in choosing from various highway sections alternatives a life cycle cost analysis (LCCA) is usually incorporated in the planning and design stages. Subsequently, the LCCA can be used in comparing and judging the efficiency of different design alternatives. The life cycle cost analysis takes into consideration the construction cost, the maintenance cost and the users' cost. To ensure sustainability of the highway throughout its life cycle apart from incorporating the users' cost, the delay cost, vehicle operating cost, accident cost, the environmental cost (energy use, emissions, waste, noise and water pollution), a weighting criteria that measures the use of renewable resources is also incorporated. Consequently, due to the growing need to the addition of environmental sustainability factor to the highway design process, environmental pollution cost are taken into consideration in the user cost. Environmental cost estimates are applied to estimate pollution damage costs over the entire life cycle of the highway. These cost are related to both direct and indirect impacts to human health from air pollution either due to inhalation of air pollutants detrimental to human health or greenhouse gas emissions that results in global warming (Zhang et al., 2010).

4. Methodology

Optimizing highway alignments within specified end points has been studied in previous works (see, for example, Jha et al. 2006; Jha and Schonfeld 2004; and Kang et al. 2012$2013). In previous formulations a uniform average unit maintenance cost was assumed which was multiplied by the length of the highway to arrive at the total life-cycle maintenance cost. Kang et al. (2012) provided the most recent maintenance cost (C_M) formulation incorporated into the highway alignment model, which is given as follows:

$$C_M = C_{HM} + C_{BO} \quad (1)$$

where: C_{HM} = Maintenance cost for highway basic segments
C_{BO} = Bridge maintenance cost

$$C_{HM} = \left(L_n - \sum_{i=1}^{n_{BG}} l_{BG_i} \right) \times K_{AM} \quad (2)$$

where: l_{BG_i} = Length of i^{th} highway bridge
n_{BG} = Total number of highway bridges in a new highway
K_{AM} = Average highway maintenance cost per unit length

$$C_{BO} = \sum_{i=1}^{n_{BG}} l_{BG_i} K_{AB} \quad (3)$$

where: K_{AB} = Average bridge maintenance cost per unit length

As can be seen in the above formulation a uniform average unit maintenance cost K_{AM} is assumed for the entire highway segment. But, it is well acknowledged that different segments of the highway may deteriorate differently due primarily to different traffic loads, and weather and accident exposures (Jha 2008; Maji and Jha 2007).

In this paper we modify maintenance cost in Eq. (1) as follows:

$$C_M = \sum_{j=1}^{t} \frac{1}{(1+r)^t} \sum_{i=1}^{n} L_i \left[a + 365 T_j b \right] \quad (4)$$

where: r = assumed interest rate (%); t = number of years of the analysis; n = total number of highway sections; L_i = length of the i^{th} section of the highway (m); a = user-specified constant which has the units of \$/m-year; T=traffic growth factor; b = a user-specified constant which has the units of \$/vehicles-m-year. The above formulation has been modified from Jha and Schonfeld (2003) by dropping the terms attributed to side-slopes since for macro-level analysis effects of side-slopes may be ignored.

5. Examples

Using the above formulation a joint minimization of initial and life-cycle maintenance cost was performed to optimize highway alignments with input data shown in Table 1 below. The values of a and b were taken as 10 and 20, respectively. A genetic algorithm was used for performing the optimization details of which are available in Jha, et. al (2006). We ran the results both without considering the maintenance cost (i.e., initial cost only) and with considering the maintenance cost. The optimal alignments are shown in Figures 1 and 2, respectively.

Table 1. Key Input Variables of the Example Study

Input Variable	Value
Elevation of starting point	100 ft.
Elevation of ending point	120 ft.
Alignment width	60 ft.
Design speed	70 mph
Maximum superelevation rate	0.06
Unit pavement cost	$20/ft.
Unit cut cost	$35/cubic yard
Unit fill cost	$20/cubic yard
Analysis period	30 years
Interest rate	6%
Traffic growth factor	3% annually
Annual average daily traffic	20,000
Maximum allowable grade	5%

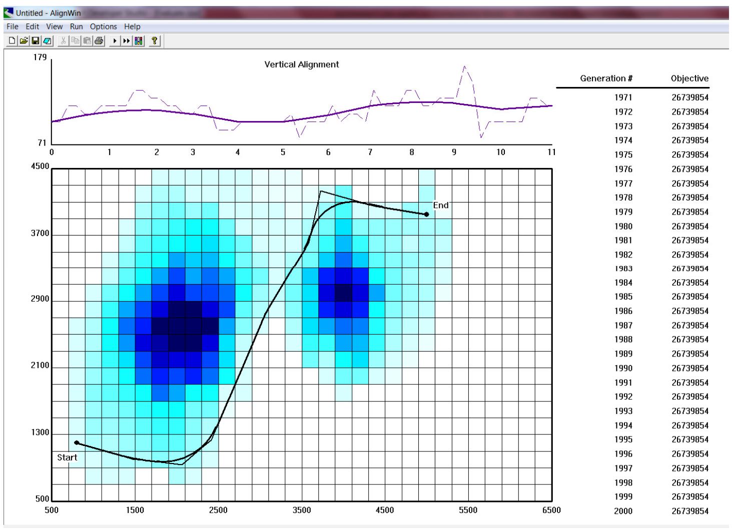

Fig. 1. Optimal horizontal and vertical alignments with Initial cost optimization only
(The optimal objective function was found to be $26.74 million after 2,000 generations of search.)

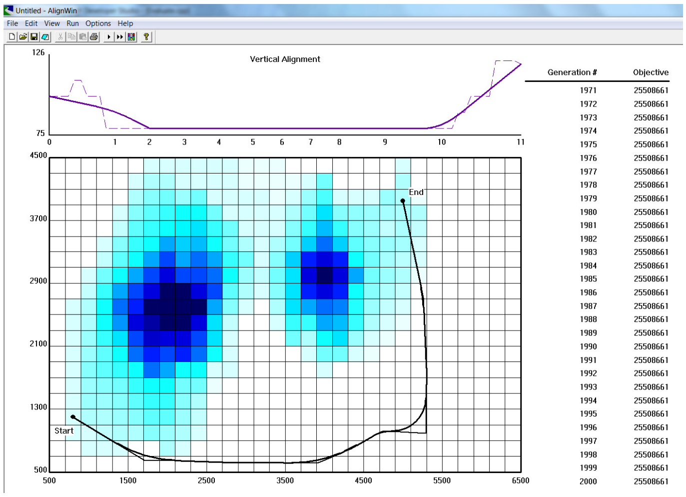

Fig. 2. Optimal horizontal and vertical alignments with the joint optimization of initial and maintenance costs
(The optimal objective function with joint optimization of initial and maintenance cost was found to be $25.51 million after 2,000 generations of search.)

6. Results and discussion

The results indicate that when maintenance cost is considered in the analysis an entirely different alignment is obtained at a cost slightly cheaper than that obtained without considering maintenance cost. This means if all factors are the same one may come up with a sustainable highway solution if life-cycle maintenance cost is incorporated in the planning stages of highway corridor analysis. Also, the routes of the alignment do not have to be the same if different solutions with and without maintenance cost are sought.

7. Conclusions and future works

A better result may be obtained by further refining the maintenance cost formulation since it is well acknowledged that different segments of the highway may deteriorate differently due primarily to different traffic loads, and weather and accident exposures (Jha 2010; Maji and Jha 2007).

An overview of the modified maintenance cost formulation which will be incorporated in the highway alignment optimization process in future works is presented below:

Different pavement segments will deteriorate differently due to the variability in traffic flow and random disturbance due to factors, such as weather and accidents. Therefore, the objective function represented by Eq. (1) will have to be modified to account for the variability in deterioration rates. As noted by Maji and Jha (2007) the solution for the optimum maintenance schedule greatly depends on the deterioration function and maintenance cost function of the pavement sections. They formulated a deterioration model which evaluated the condition of an element on a scale of 1 to 0. The condition of the new element was represented as 1 and 0 at the end of its life-cycle. Therefore, the condition of the elements at any point of time would depend on the life-cycle of the element and the time of observation. If the life-cycle of the pavement is l_c then in the t^{th} year the condition of the element will be $f(t,l_c)$. One of the simplest mathematical functions that can display the pavement's deterioration properties considered is the parabolic function. Thus, the condition of a pavement can be formulated as follows:

$$q_t = f(t,l_c) = 1 - \frac{t^2}{a} \tag{5}$$

where,

q_t = Condition of the element in the t^{th} year

a = A constant chosen in such a way that the condition is 0 at end of the life-cycle

In order to account for the demand variability and randomized disturbance, the deterioration is assumed to be different for each pavement segment k (k=1,2,...,K) and is a function of traffic flow and random disturbance. Therefore, the above formulae is modified as follows:

$$q_k^t = f_k(t,x,d,l_c) = 1 - \frac{t^2}{a_k(x,d,t)} \tag{6}$$

where a is not treated a constant any more, rather it is now treated as a variable specific to each pavement section whose value depends on the amount of traffic flow in a given year x, and random disturbance d.

The M&R activity improves the condition of the pavement section. The amount of improvement decreases with the age of the pavement and is generally less than the amount of deterioration at any point of time. After performing the M&R activities, the condition of the element in the t^{th} year will improve. The amount of improvement will depend on the condition of the element in the t^{th} year without any M&R activity and the total amount of improvement until that time. The total amount of improvement (I_T) till the T^{th} year can be found by the following formulation:

$$I_T = \sum_{t=1}^{T} I_t = \sum_{t=1}^{T} \alpha_t \times r_t \tag{7}$$

where,

$$\alpha_t = \begin{cases} 1 \text{ if maintainedin the } t^{th} \text{ year} \\ 0 \quad \text{otherwise} \end{cases}$$

Hence, the present condition of the k^{th} pavement in the t^{th} year can be mathematically represented as follows:

$$Q_k^t = f(q_k^t, I_k^t) = q_k^t + I_k^t \tag{8}$$

The maintenance cost of the k^{th} pavement will be the function of the number of years, t and the threshold condition, H of the element. Similar to Maji and Jha's (2007) approach a parabolic function can be considered to represent the maintenance cost, which is represented as follows:

$$c(k,i,j,t) = f(k,i,j,H,t) = \frac{t^2}{b(i,j,H)} \quad (9)$$

where,

$b(k,i,j,H)$ = A constant chosen in such a way that the maintenance cost at the threshold condition is equal to the cost of the newly repaved surface

When the element is repaved, the future maintenance cost should also decrease compared to maintenance cost with no previous history of pavement. The amount of decrease in maintenance cost will decrease with the age of the element and it should be equal to 0 when the pavement reaches the threshold condition. The amount of decrease in maintenance cost due to maintenance in the t^{th} year can be mathematically represented as follows:

$$c_{d_k}^{t} = f(t, c_k^t, H) = c_{d_k}^{t}\left(1 - \frac{t^2}{d}\right) \quad (10)$$

where,

d = A constant chosen in such a way that it will be equal to t^2 when the condition in t^{th} year reaches the threshold condition

Therefore, the present maintenance cost at any point of time with previous history of maintenance is given as follows:

$$c_{p_k}^{t} = f(t, c_{k_i}^t, c_{d_k}^t) = c_k^t - \sum_{t=1}^{T-1} x_k^t \times c_{d_k}^{t} \quad (11)$$

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