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Probabilistic Lifecycle Assessment as a Network-Level Evaluation Tool for the Use and Maintenance Phases of Pavements

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1.1. ABSTRACT

Agencies that manage pavement networks have a role in mitigating the factors that affect global climate change by managing their networks in such a way that these factors are minimized. Whereas much research is still required in order to quantify the climate change impact of many variables relating to pavements, the impact of pavement condition on vehicle fuel consumption has been clearly demonstrated in several recent research projects. In light of extensive research that has shown that pavement characteristics have a significant impact on vehicle fuel consumption, it can be shown that maintaining a network of pavements to minimize roughness can potentially limit the energy consumption of vehicles travelling on the pavement network. The objective of this paper is to demonstrate a method by which transportation agencies can measure the impact of their management decisions towards reducing the energy consumption of their network. The use of an LCA to probabilistically quantify energy consumption for a given set of expected maintenance actions defined at the network-level will be demonstrated. Furthermore, it will be shown how the results of the LCA can be used to evaluate the energy consumption attributed to the pavement network over a defined time frame.

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1.2. INTRODUCTION

Agencies that manage pavement networks have a role in mitigating the factors that affect global climate change by managing their networks in such a way that these factors are minimized. To this end, the United States Federal Highway Administration (FHWA) has committed itself to mitigating climate change factors, such as the reduction of energy consumption attributed to the pavement network (FHWA 2013). It has been established that the majority of the energy consumed during the lifecycle of a pavement occurs during the use phase of the road (i.e., after the road has been opened to traffic), and only 2 to 5 percent of the energy is consumed during construction, maintenance and operation (i.e., lighting and traffic controls) EAPA/EuroBitume (2004). Variables that most impact the energy consumed during the use phase include fuel consumption as a function of pavement condition, heat island effect of the pavement, effect of pavement albedo and others. Whereas much research is still required in order to quantify the climate change impact of many of the variables, the impact of pavement condition on vehicle fuel consumption has been clearly demonstrated in several recent research studies. In light of extensive research that has shown that pavement characteristics have a significant impact on vehicle fuel consumption, it can be shown that maintaining a network of pavements to minimize roughness (as measured by the International Roughness Index (IRI)) can potentially limit the energy consumption of vehicle travelling along the pavement network.

In order to quantify such factors as energy consumption of a system or greenhouse gas emissions, a lifecycle assessment (LCA) is generally employed. LCA's are methods that are used to systematically and clearly evaluate the inputs and resulting outputs of a system. In the context of pavements, LCA's have generally been deterministic in nature and left for project-level evaluation (Zapata and Gambatese 2005; Huang et al. 2009; Patrick and Arampamoorthy 2010*;* Weiland and Muench 2010). The use of an LCA to probablistically quantify energy consumption for a given set of expected maintenance actions defined at the network-level will be demonstrated in this paper.

The application of probablistic approaches to assess the impact of pavement management alternatives has been demonstrated in several applications (Harvey et al. 2012; Chen and Flintsch 2012; Tighe 2012). Among the cited benefits of a probablistic approach to life cycle cost analysis is the ability for the decision makers to evaluate the risks associated with the alternatives given uncertainty in model parameters and measured variables. Defining the expected energy consumption probablistically is important given the large uncertainties that exist in many of the varibles, such as traffic growth and the change of the pavement IRI over time. Furthermore, it will be shown how probablistic results of an LCA can be used to evaluate the energy consumption attributed to the pavement network over a defined time frame.

1.3. OBJECTIVE

The objective of this paper is to demonstrate a probabilistic approach by which transportation agencies can measure the impact of the uncertainties associated with management decisions while working towards reducing the energy consumption of their pavement networks. The methods presented in this paper are for a network-level evaluation of the impact of project selection on the energy consumption attributed to the pavement network. However, the excess energy consumption due to congestion during maintenance will not be included in the process presented in this paper. This paper will focus on flexible pavements, but it is expected that a similar method can be employed to evaluate Portland cement concrete (PCC) and composite pavements. A process based LCA approach is used to assess the energy consumption. The process based approach is defined in the International Standards Organization (ISO) standard ISO 14040 and ISO 14044, Standards for a Process-Based LCA Approach.

1.4. BACKGROUND

The purpose of a pavement LCA is to quantify the total environmental impact of the pavement throughout its life, which is generally divided into the following five phases (after Santero et. al. 2011): (1) raw materials and production; (1) construction; (3) use; (4) maintanenance and (5) end of life. An important consideration for LCA is the boundaries chosen for the analysis. Ideally, an LCA is a cradle to grave analysis that accounts for the entire life of the pavement, all the processes involved with the system, as well as other processes impacted by the system. However, lack of information and an inability to accurately predict certain parameters, such as material life and the impact of the system condition on the user, sometimes lead to a constraint on the system boundaries for a pavement. Thus, in the case of pavements, typical LCA boundaries are constricted to cover only the time period from material extraction through the end of the construction phase of the project.

The first two phases of a pavement LCA, material production and construction, have been the focus of extensive research. For example, Pavement Life Cycle Assessment Tool for Environmental and Economic Effects (PaLATE) is a spreadsheet based tool that was developed to account for both economic and environmental factors related to the construction processes of a pavement (Horvath 2003). For the environmental assessment, PaLATE assesses emissions associated with the production of materials, construction, material transport, maintenance and a database of recycled materials built in. As another example, Park et al. (2003) evaluated the environmental loads due to the processes throughout the lifecycle of a highway, defined in four stages as: (1) manufacturing of materials, (2) construction, (3) maintenance and (4) end of life (demolition/recycling), but notably the use phase is excluded from this definition of the pavement lifecycle. The researchers focused on energy consumption, then used appropriate factors to translate the energy consumption into equivalent emissions and estimate pollutant discharge into water. A few other notable LCA studies relating to the first two phases of the lifecycle are Zapata and Gambatese (2005), Huang et al. (2009) and Patrick and Arampamoorthy (2010).

Much of the research pertaining to the use phase of the pavement (the third phase of an LCA) has been to quantify the effect of rolling resistance on emissions and energy consumption from vehicles travelling on the pavement. Several research projects with the objective of quantifying the impact of pavement properties on rolling resistance have been undertaken, and some research has shown that in all driving conditions, an overall average of 25 percent of fuel consumption is expended on rolling resistance leaving 75 percent to overcome air drag and inertia (Izevbekhai 2012). Thus, if the rolling resistance of a pavement were reduced, the vehicle fuel consumption along that pavement would be reduced. Furthermore, a 10 percent reduction in rolling resistance can lead to between a 1 and 2 percent reduction in fuel consumption, which also leads to a reduction of greenhouse gas emissions (Transportation Research Board 2006; Evans et al. 2009). The tire-pavement interaction is the main factor in rolling resistance, and is impacted by several variables such as macro-texture, pavement stiffness, roughness, rutting and the transversal slope of the pavement. Relatively good relationships have been developed to determine the impact of IRI and macro-texture, as measured by the mean profile depth (MPD), on a vehicles rolling resistance (Chatti and Zaabar 2012; Karlsson et al. 2012).

Chatti and Zaabar (2012) reported the results of calibrating the HDM 4 models for vehicle operating costs in the National Cooperative Highway Research Program (NCHRP) report 720, and their research clearly demonstrates the relationship between fuel consumption and pavement factors such as its IRI and mean pavement depth (MPD), which is a measure of surface texture. Within the scope of this paper, the influence of the pavement IRI on fuel consumption will be the only factor considered for the use phase. It is important to note that the MPD of the pavement is known to play a role in pavement safety (Flintsch et al. 2003). Thus, reducing the MPD of the pavement in order to reduce fuel consumption may come at the tradeoff of safety to the travelling public. This aspect is not addressed in this paper.

1.4.1. Uncertainties in Pavement Management

Uncertainties are an inevitable part in every analysis conducted by a transportation agency, and are typically a result of predicting current and future values in the face of limited information and using models of assumed future behaviors. Economic uncertainties in the form of agency costs typically exist in many forms; namely, uncertainties associated with project construction costs, discount rate, costs of future treatments, life of the treatments (in determining next treatment timing) and salvage or remaining value. User cost uncertainties (defined by user delay) generally arises from uncertainties in the current and projected traffic volumes and composition, road user behavior (carpool, no-show, detour, etc.), value of time by vehicles type, as well as uncertainties in the estimation of congestion delay time and construction duration. In light of these uncertainties, one of two approaches is used to perform a lifecycle cost analysis: (1) a deterministic analysis where expected values are used and solutions are presented as fixed; or (2) a probabilistic assessment that utilizes some form of simulation (e.g., Monte Carlo Simulation as described by Herbold (2000)) and solutions are represented by distributions of possible values.

Uncertainties relating to environmental measures include; uncertainties about the environmental impacts for a given project, uncertainties in the prediction models relating the environmental impacts during the use phase (e.g., the relationships between IRI and fuel consumption), uncertainties in the prediction of future pavement properties and uncertainties about current and future traffic characteristics. Similar to the economic uncertainties, it is expected that the environmental performance measures can be addressed either through a deterministic assessment or through probabilistic simulation. This paper will address the probabilistic assessment of the environmental factors.

Many of the uncertainties can be described by distributions of possible values in a probabilistic assessment. For example, Perrone et al. (1998) describes the use of a triangular distribution in lifecycle cost analysis to simulate treatment life, given that minimum, expected and maximum values are generally known for a treatment life. Similar parameters are known for future prediction models of pavement parameters (e.g., IRI and traffic characteristics), and thus a similar probabilistic assessment may be employed where distributions are assigned based on mean values and the nature of the known or expected variance in the variables.

1.5. Defining the Energy Consumption Attributed to Maintenance Actions

An important consideration is that the level of detail of information used at the network-level is lower than that at the project-level. Whereas project-level analysis is done using greater detail about a specific location, at the network-level work types and costs are generalized estimates for a large network of pavements until further investigation is done at the project-level for a specific project. For example, the Virginia Department of Transportation (VDOT) uses a set of matrices and filters based on pavement condition to choose work types at the network-level, and generalizes the work types into: Do Nothing; Preventative Maintenance; Corrective Maintenance; Restorative Maintenance and Rehabilitation/Reconstruction (VDOT 2008). Each of the work types have an accompanying expected cost and expected life used in network-level analysis. This principle will hold true for environmental considerations, where expected environmental loads of the different maintenance actions can be estimated probabilistically given expected values and deviations from the expected values. For example, if Corrective Maintenance is generally characterized by a mill and overlay, an expected environmental load can be estimated per unit area treated.

1.5.1. Maintenance Actions

The maintenance actions used by VDOT for network-level pavement management are used to quantify the energy consumption in this paper. The maintenance actions defined in Table 0-1 are used for network-level planning purposes, and the various category levels are triggered based on the pavement condition, distress types present and the structural condition of the pavement (VDOT 2008).

Table 0-1 VDOT Maintenance Actions for Network-Level Decision Making (adapted from (VDOT 2008))

Category	Activities
Do Nothing (DN)	N/A
Preventive Maintenance (PM)	1. Minor Patching (<5% of Pavement Area: Depth 2”)
	2. Crack Sealing
	3. Surface Treatment (e.g., Chip Seal, Microsurface, etc.)
Corrective Maintenance (CM)	1. Moderate Patching (<10% of pavement area: Depth 6”)
	2. Partial Depth Patching (<10% of Pavement Area: Depth 4”-6”) and Surface Treatment
	3. Partial Depth Patching (<10% of Pavement Area: Depth 4”-6”) and Thin (≤ 2”) AC Overlay
	4. ≤ 2” Milling and ≤ 2” AC Overlay
Restorative Maintenance (RM)	1. Heavy Patching (<20% of Pavement Area: Depth 12”)
	2. ≤4” Milling and Replace with ≤4” AC Overlay
	3. Full Depth Patching (<20% of Pavement Area: Depth 9”-12”) and 4” AC Overlay
Rehabilitation /Reconstruction (RC)	1. Mill, Break and Seat and 9”-12” AC Overlay
	2. Reconstruction

For the purposes of this paper, PM will be represented by Microsurfacing, CM will be represented by a distribution approximating a two inch mill and overlay, RM will be represented by a distribution approximating a four inch mill and overlay and RC will be represented by a distribution approximating a ten inch mill and overlay with re-compaction of the subgrade. Each of the maintenance actions will also be represented with uncertainty to signify that assumptions are made about the extent of work done.

1.5.2. Energy Consumption

A literature review was conducted in order to define the energy consumption related to the various processes within the construction phase of a pavement. Using the processes for the construction phase, a subset of processes was defined for the maintenance activities (following (Wang et al. 2012)). The expected energy consumption for each process in the maintenance actions is shown in Table 0-2.

Table 0-2 Energy Values for Materials and Processes

Phase	Process	Energy[a] (Energy has been converted to common units from cited reference)	Energy
Removal	Mill Asphalt	11.12 MJ/Ton (Patrick and Arampamoorthy 2005)	4,550 MJ/lane-mile/inch
	Loading Material	3.2 MJ/Ton (Horvath 2003)	1,310 MJ/lane-mile/inch
Aggregate Production	Aggregate Production	38 MJ/Ton (Crushed) (Cerea 2012)	14,770 MJ/lane-mile/inch[b]
Bitumen Production	Bitumen Production	5,450 MJ/Ton (Zapata and Gambatese 2005)	111,500 MJ/lane-mile/inch[b]
HMA Production	Production Process	318 MJ/Ton (Zapata and Gambatese 2005)	130,125 MJ/lane-mile/inch
HMA Paving	SubGrade Compaction	0.58 MJ/yd2 (Patrick and Arampamoorthy 2005)	7,040 MJ/lane-mile
	Application of Tack Coat (Including Material Energy)	3260 MJ/lane-mile[c]	3,260 MJ/lane-mile
	Paving	2.23 MJ/Ton (Patrick and Arampamoorthy 2005)	913 MJ/lane-mile/inch
	Rolling	1.4 MJ/Ton (Horvath 2003)	573 MJ/lane-mile/inch
Slurry Equipment (PM)	Placement of Microsurfacing	2470 MJ/lane-mile (Giustozzi et al. 2012)	2470 MJ/lane-mile
PM Materials - Assumed Microsurfacing	Combined Energy of Mix Design[d]	34.07 MJ/m2 (Cerea 2012)	200,548 MJ/lane-mile
Hauling Materials	Transport	13.34 MJ/veh-km for 35.3 Ton Load (Patrick and Arampamoorthy 2005)	21.5 MJ/veh-mile per 35.3 Tons

a. Mean value used when multiple values are reported.

b. Asphalt mix was assumed to be composed of 5% binder by weight and 95% aggregate by weight. No reclaimed asphalt was factored into the calculation. 130 lb/ft3 Assumed Unit Weight for Aggregate, 155 lb/ft3 Assumed Unit Weight for Asphalt.

c. 1 tack truck=26.5 L/h Fuel *(3)*; Expected 0.13 liters per yd^2 Application (50% asphalt mixture) (http://pavementinteractive.org/index.php?title=Tack_Coats), 1mile/hr.

d. 11% Modified Emulsion Binder, 82% Aggregate, 1% Filler, 6% Water *(24)*.

1.5.3. Assessment of Energy Consumption per Maintenance Action

Several uncertainties exist during the network-level analysis, and these uncertainties should be accounted for during the assessment of the expected energy consumption of the maintenance action. Some examples of uncertainties include uncertainty about the extent of maintenance (e.g., the predicted thickness of the overlay at the network-level may not be the same as when determined at the project-level) and uncertainties about the hauling distances for the materials. In general, these uncertainties can be accounted for by introducing the variables as distributions as opposed to deterministic values. For example, if CM is defined as in Table 0-1 as less than or equal to a two inch mill and overlay, then a potential representation of the variable may be as a normal distribution with a mean of 1.7 inches and a standard deviation of 0.4 inches. In this case, 77 percent of the time the actual overlay will be less than two inches, 2 percent of the overlays will be greater than 2.5 inches and 96 percent of the overlays will be over one inch thick. Thus, the uncertainty in predicting CM at the network-level is addressed by assuming that the majority of the time the overlay will fall between one and 2.5 inches thick, with some outliers as expected.

Another uncertainty that must be addressed is whether the amount of milled asphalt is equivalent to the depth of the overlay. In many cases, particularly where clearance is not an issue, an agency might not wish to expend the resources to mill to the same depth as the overlay. This assumption impacts both the energy consumption assumed for the milling and the transportation amount for disposal, which may add up to a significant portion of the expected energy consumption for the maintenance treatment. In order to address this, the amount milled was made a function of the thickness of the overlay by defining it as a single peaked triangular distribution with a minimum of half the thickness and a maximum value and expected value equal to the thickness of the overlay.

There are also a number of uncertainties associated with the energy consumption of the equipment and material manufacturing. The uncertainties within the quantities were addressed by assuming the energy per unit as a normal distributed variable with an assigned standard deviation. In general 10 percent of the mean was assigned as the standard deviation, thus approximately 95 percent of the data fell between 0.8 and 1.2 times the mean value. The distributions of the variables used in the analysis are given in Table 0-3.

Given that the inputs to the system are uncertain, the calculated energy consumption will also be represented by a distribution. In order to calculate the distributions of the energy consumption for the different maintenance actions, the Monte Carlo simulation method was used. Readers are referred elsewhere for a detailed discussion of the Monte Carlo method (e.g., (Metropolis and Ulam 1949). However, the basic steps of the Monte Carlo method can be generalized as follows: (1) Assume the distribution of input variables is known; (2) sample each distribution of input variable independantly; (3) calculate an output and (4) repeat over a large number of iterations. The Monte Carlo method has been used in pavement management in terms of analyzing proabalistic life cycle costs (FHWA 2004), and allows many types of distrubtions to be combined within a single analysis. In order to determine the distribution of energy consumption for each of the maintenance actions, a set of MATLAB™ codes were developed and will be made available to the reader for download upon request. The result of the Monte Carlo method is a distrubtion or histogram of potential outcomes based on the distributions defined for the input values. The histograms of the energy consumption per lane-mile for the the various maintenance actions is shown in Figure 0-1.

Table 0-3 Distributions Used in Analysis of Maintenance Actions

	PM	CM	RM	RC
Overlay Thickness (OL)	N/A	Normal[1.8,0.4] inches	Normal[3.6,0.5] inches	Normal[9,1.5] inches
Mill Thickness (mill)	N/A	Triangular Distribution [0.5*OL,OL,OL] [b]	Triangular Distribution [0.5*OL,OL,OL] [b]	Triangular Distribution [0.5*OL,OL,OL] [b]
Mill Energy	N/A	Normal[4550*mill ,450*mill] MJ/lane-mile [c]	Normal[4550*mill ,450*mill] MJ/lane-mile [c]	Normal[4550*mill ,450*mill] MJ/lane-mile [c]
Loading Material Energy	N/A	Normal[1310*mill ,130*mill] MJ/lane-mile [c]	Normal[1310*mill ,130*mill] MJ/lane-mile [c]	Normal[1310*mill ,130*mill] MJ/lane-mile [c]
Aggregate Production	N/A	Normal[14770*OL,1477*OL] MJ/lane-mile	Normal[14770*OL,1477*OL] MJ/lane-mile	Normal[14770*OL,1477*OL] MJ/lane-mile
Bitumen Production	N/A	Normal[111500*OL,11150*OL] MJ/lane-mile	Normal[111500*OL,11150*OL] MJ/lane-mile	Normal[111500*OL,11150*OL] MJ/lane-mile
Production Process	N/A	Normal[130125*OL,13012*OL] MJ/lane-mile	Normal[130125*OL,13012*OL] MJ/lane-mile	Normal[130125*OL,13012*OL] MJ/lane-mile
SubGrade Compaction	N/A	N/A	N/A	Normal[7040,704] MJ/lane-mile
Application of Tack Coat (Including Material Energy)	N/A	Normal[3260,326] MJ/lane-mile	Normal[3260,326] MJ/lane-mile	Normal[3260,326] MJ/lane-mile
Paving	N/A	Normal[913*OL,91*OL] MJ/lane-mile	Normal[913*OL,91*OL] MJ/lane-mile	Normal[913*OL,91*OL] MJ/lane-mile
Rolling	N/A	Normal[573*OL,57*OL] MJ/lane-mile	Normal[573*OL,57*OL] MJ/lane-mile	Normal[573*OL,57*OL] MJ/lane-mile
Placement of Preventive Maintenance (Equipment)	Normal[2470, 247] MJ/lane-mile	N/A	N/A	N/A
Combined Energy of Mix Design for Preventive Maintenance	Normal[200548, 20055] MJ/lane-mile	N/A	N/A	N/A
Transport Distance	Uniform [1 mile, 50 mile]	Uniform [1 mile, 50 mile]	Uniform [1 mile, 50 mile]	Uniform [1 mile, 50 mile]
Transport Amount - Disposal	N/A	Normal[409*mill,41*mill] MJ/lane-mile [d]	Normal[409*mill,41*mill] MJ/lane-mile [d]	Normal[409*mill,41*mill] MJ/lane-mile [d]
Transport Amount - Aggregate to Plant	Normal[200,10] Tons/lane-mile [a]	Normal[343*OL,34*OL] MJ/lane-mile [e]	Normal[343*OL,34*OL] MJ/lane-mile [e]	Normal[343*OL,34*OL] MJ/lane-mile [e]
Transport Amount - Plant to Site	Normal[200,10] Tons/lane-mile [a]	Normal[409*OL,41*OL] MJ/lane-mile [d]	Normal[409*OL,41*OL] MJ/lane-mile [d]	Normal[409*OL,41*OL] MJ/lane-mile [d]

[a] 0.0283 tons/yd^2 per (Cerea 2010); [b] OL refers to the thickness of overlay (inches); [c] Mill refers to the thickness milled (inches); [d] Density of asphalt was assumed as 155 pounds per cubic foot; [e] Aggregate density was assumed as 130 pounds per cubic foot

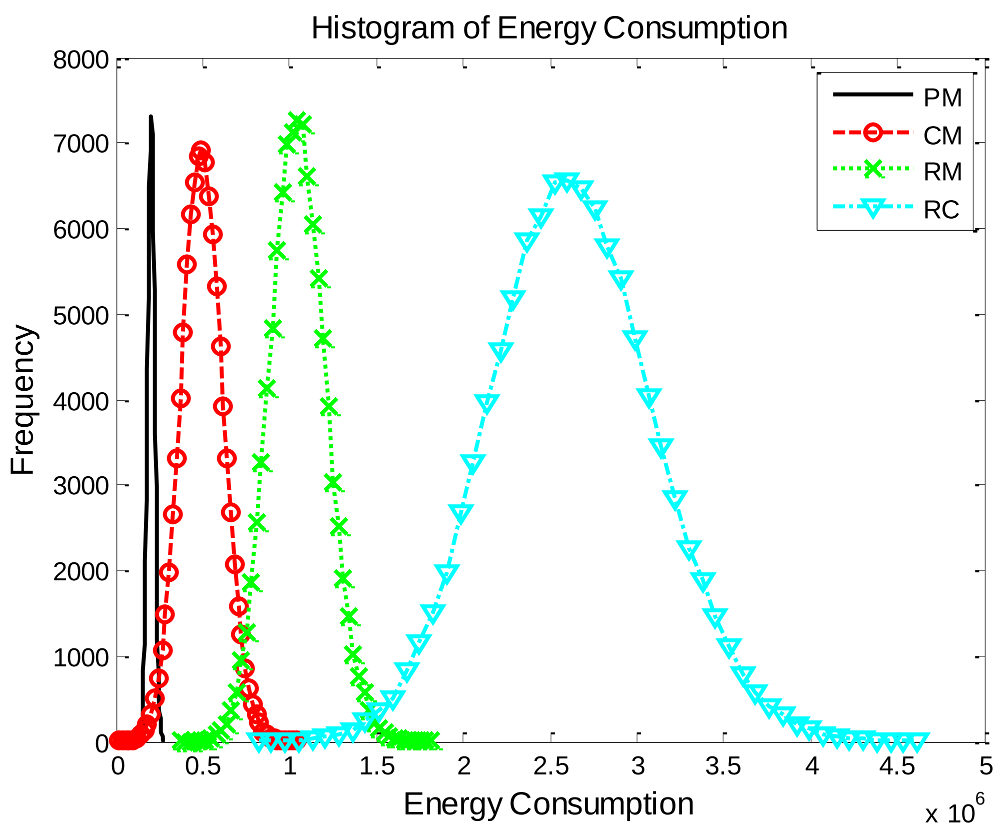


Figure 0-1 Energy Consumption for Maintenance Actions in Mega Joules (MJ)

1.6. ENERGY CONSUMPTION DURING THE USE PHASE

The energy consumption during the use phase of the pavement comes in the form of fuel consumed by vehicles travelling over the pavement. Furthermore, the condition of the pavement impacts the fuel consumption of the vehicles by increasing the rolling resistance of the vehicles travelling along the pavement. This effect has been quantified in the NCHRP report 720 and accompanying software by Chatti and Zabaar (2012). The impact of the IRI of the pavement on excess fuel consumption will be the variable assessed for the use phase in this paper.

In order to quantify the impact of the roughness on fuel consumption, a baseline roughness must be set. It is important to note that the roughness of a pavement after construction is not zero. McGhee and Gillespie (2006) reported that pavements subject to a smoothness specification had an initial roughness of 67.4 in/mile with a standard deviation of 10.2. Those pavements not subject to the specification had an initial roughness of 76.2 in/mile with a standard deviation of 11.5. Furthermore, the reported average increase in IRI over a 7 year period was 1.23 in/mile/year. An initial IRI of 70 in/mile with a standard deviation of 10 will be used in this paper, and a triangular distribution with a range of ± 1.5 times the standard deviation from the mean will represent the IRI after the maintenance action. Thus, a minimum value of 55 in/mile will be considered for the fuel consumption calculations. Furthermore, the growth rate of IRI as a function of time will be assumed as a nomally distributed variable with a mean of 1.25 in/mi-yr and a standard deviation of 0.13.

In order to run the model developed by Chatti and Zabaar (2012) to determine the additional fuel consumption as a function of IRI, the mean texture depth was held at 0.05 inches, the grade and super-elevation were left at 0 percent, the pavement type was asphalt, the speed was assumed at 55 mph and the air temperature was assumed as 68 degree Fahrenheit. These variables were input into the software that accompanies the National Cooperative Highway Research Program (NCHRP) report 720 (Chatti and Zabaar 2012), and the impact of roughness on the fuel consumption was assessed over a range of roughness values between 55 in/mile to 120 in/mile. The values used for the combustion energies of gasoline and diesel were 132 MJ/Gallon and 146 MJ/Gallon respectively.

1.6.1. Network-Level Evaluation

In order to demonstrate the evaluation of energy consumption at the network-level during the use phase, an example network of roads was developed (Table 0-4). In this case, the energy consumption is a function of the road length, AADT, the percentage of trucks, the roughness and construction type. The length of the roads and the initial roughness of the roads were taken as deterministic values because it can be assumed that the roughness values in this case were measured just prior to the analysis. The traffic values were treated as normally distributed variables with a standard deviation of 1,000, and the percentages of trucks were set within the range typically found on highly travelled interstate routes (e.g., Interstate 81 in Virginia). The condition values are indices representing the overall functional condition of the pavement (i.e., a combination of cracking, rutting, etc.), where a value of 100 represents a pavement with no distresses and a value of 0 represents the worst case condition. The results from analyzing the energy consumption due to the rolling resistance from a 5 year analysis for the road network are shown in Figure 0-2. A normally distributed traffic growth rate with a 3 percent mean and a 0.3 percent standard deviation was used in the analysis, and a growth rate of the IRI as nomally distributed with a mean of 1.25 in/mi-yr and a standard deviation of 0.13. Traffic growth was calculated using compounding growth methods.

Table 0-4 Example Road Network Characteristics

Road	Length (miles)	Traffic (AADT)	Percent Trucks	Initial Roughness[a] (in/mile)	Condition	Construction
1	1.8	20,000	23%	130	65	Asphalt
2	2.2	37,000	25%	80	83	Asphalt
3	1.1	25,000	21%	77	92	Asphalt
4	2.4	12,000	27%	115	55	Asphalt
5	2.1	32,000	25%	97	73	Asphalt
6	1.6	41,000	19%	110	68	Asphalt
7	1.3	15,000	22%	65	93	Asphalt
8	1.9	30,000	24%	91	75	Asphalt

a. Roughness at the start of the analysis period

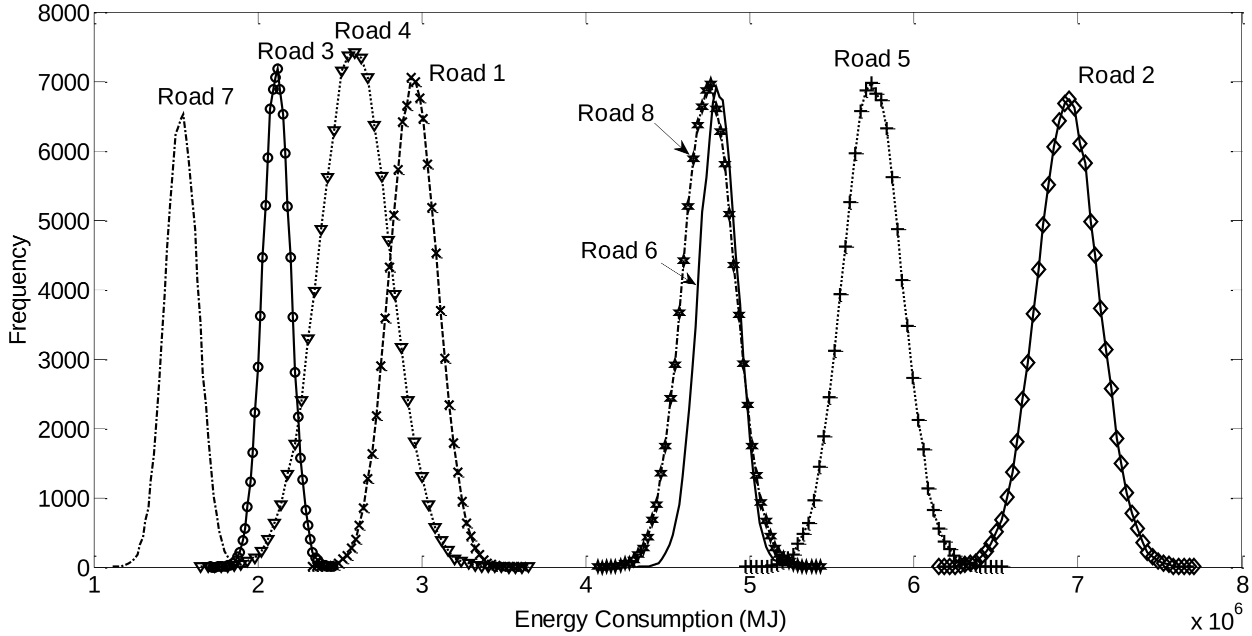


Figure 0-2 Energy Consumption for the Roads in the Network: 5 Year Analysis

1.7. MULTICRITERIA OPTIMIZATION

So far, this paper has demonstrated methods to probabilistically assess an LCA of the use and maintenance phases of the pavement at a level of detail sufficient for network-level analysis. This information has direct implications to decision making by providing both expected values for the energy consumption and distributions of probable values for the decision maker to be aware of. In an effort to contribute to climate change mitigation, the FHWA has focused resources on assuring that more sustainable decision making is promoted htrough a balanced tradeoff between environmental, economic and social factors (FHWA 2013). Thus, a sustainable decision framework should incorporate these three factors as primary considerations. One key consideration in the decision making or decision analysis process is the certainty about the outcomes, which makes a probabilistic assessment of the variables a key contributor to the decision process.

Generally, multi-objective programs using optimization techniques are employed. Multi-objective programs using an optimization technique refers to the selection of a best element from some set of available alternatives (INFORMS 2012). No single solution may be considered optimal in the case of multiple objectives, but instead a set of solutions can be found that represent a non-dominated set (referred to as a Pareto set) given different values for each objective. Any solution that falls along the Pareto set can be considered optimal, and thus the '*best*' solution depends on the amount of tradeoff between the criteria that the agency is willing to make. Three objectives will be considered in this analysis as;

$$\left[\mathbf{Min}\left(\text{Cost}\right), \mathbf{Max}\left(\text{Condition}\right), \mathbf{Min}\left(\text{Energy}\right)\right] \tag{3-1}$$

In order to demonstrate multi-objective optimization on the pavement network shown in Figure 0-4, a three year analysis was performed considering average condition of the network (over the three year time frame), total maintenance cost and energy consumption (from maintenance and rolling resistance).

The three year time frame was chosen in order to show the variations in outcomes while maintaining the constraint that each road is selected no more than once throughout the analysis period. The deterioration curve for the condition of the pavements was set as:

$$Condition(age) = a(age)^2 + b(age) + c \qquad (3\text{-}2)$$

Where age is the pavement age in years, *c* was set at 100, *a* and *b* were set as uniformly distributed variables (in order to simulate uncertainty in the deterioration modeling) that had values between [-0.216, -0.324] and [-1.536, -2.304], respectively. The energy consumption due to maintenance and cost were set as a function of the condition of the pavement where the following thresholds were set: condition above 90 was do nothing; condition between 80 and 90 set as PM and assigned a cost of $1,400 per mile; condition between 65 and 80 was set as CM and assigned a cost of $14,100 per mile; condition between 50 and 65 was set as RM and assigned a cost of $35,600 per mile; and condition less than 50 was set as RC and assigned a cost of $100,000 per mile. The costs used in the analysis were taken from (VDOT 2008) and scaled such that the maximum cost was $100,000. Approximately 1.7 million variations of maintenance plans were evaluated (i.e., choosing to maintain road *i* in year *j*), and then the surface containing the Pareto set was found by minimizing the vector length defined by the following set of points representing the normalized values of each variable (Figure 0-3):

$$\left[\frac{Energy - Energy_{Min}}{Energy_{Max} - Energy_{Min}}, \frac{Condition_{Max} - Condition}{Condition_{Max} - Condition_{Min}}, \frac{Cost - Cost_{Min}}{Cost_{Max} - Cost_{Min}}\right] \qquad (3\text{-}3)$$

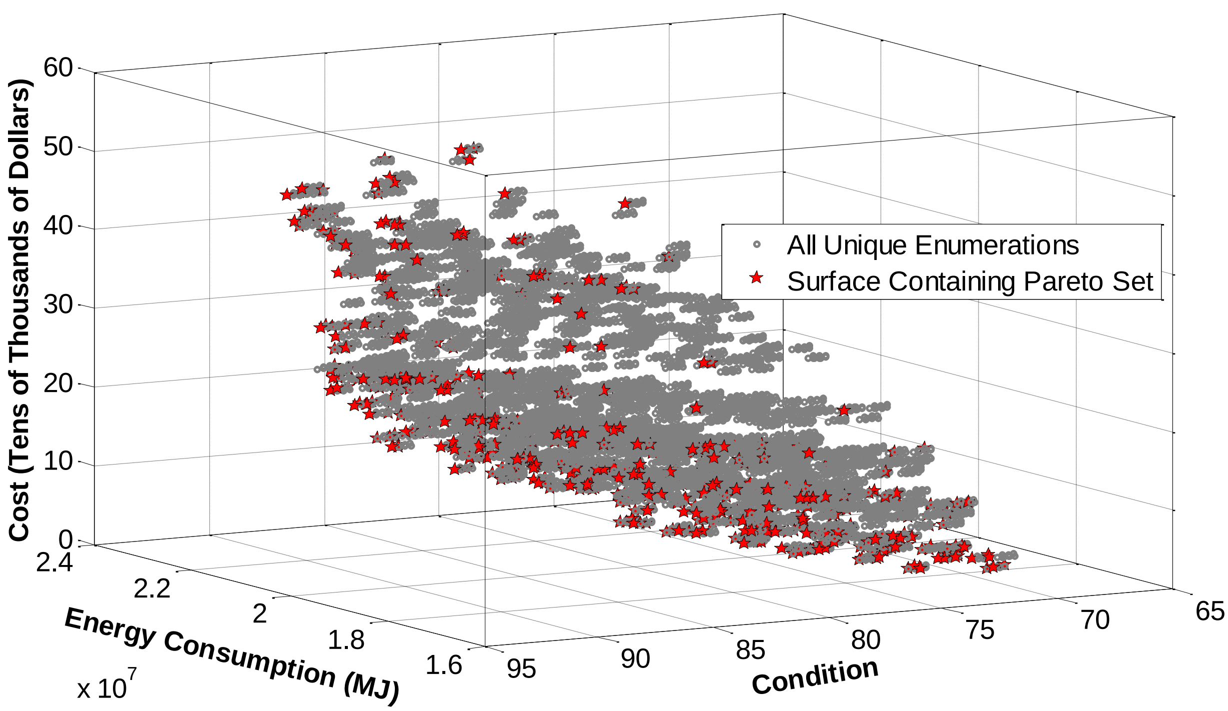


Figure 0-3 Surface Containing Pareto Set for the Alternatives for Maintenance of the Network

The data shown in Figure 0-3 are for the mean condition (i.e., the average of all of the stochastic variables). In order to demonstrate the change in the Pareto sets when the maintenance plans that form the set are evaluated probabilistically, a subset was evaluated using a 5 percentile (i.e., a 5 percent probability that the actual values will be as good as or better than the reported number) and 95 percentile level of certainty. The results are shown in Figure 0-4.

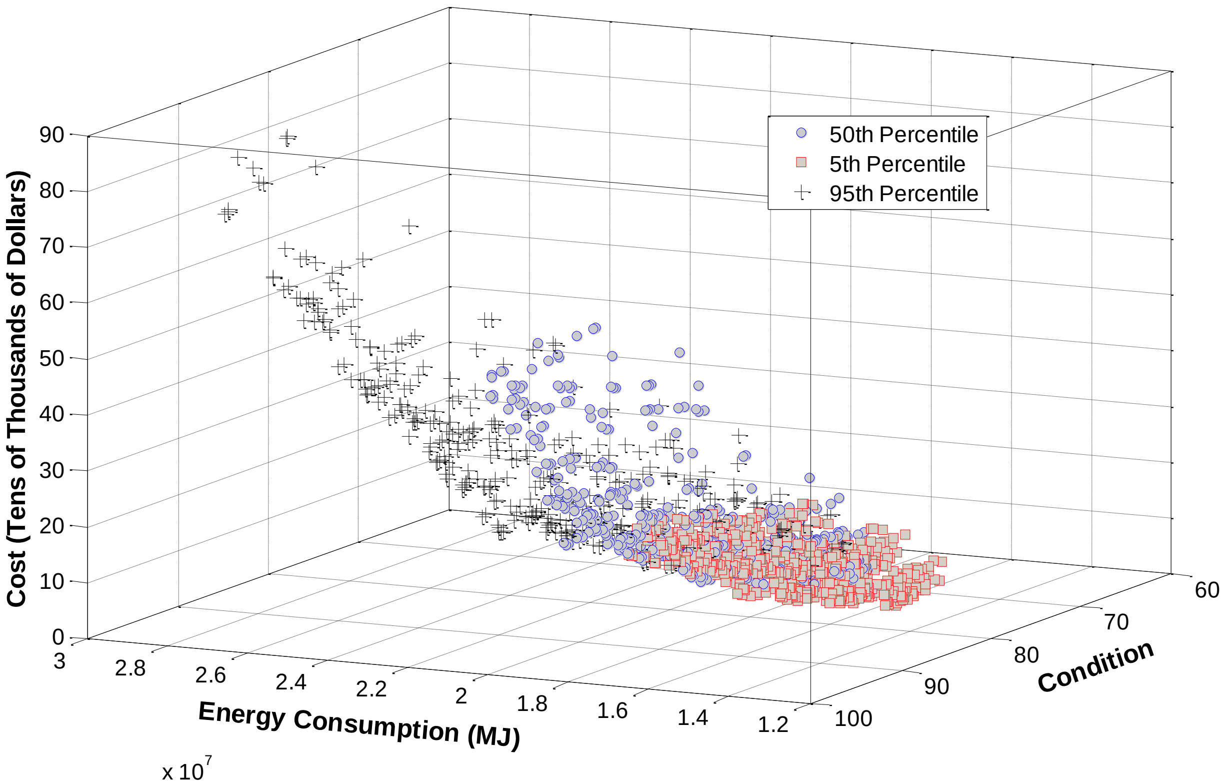
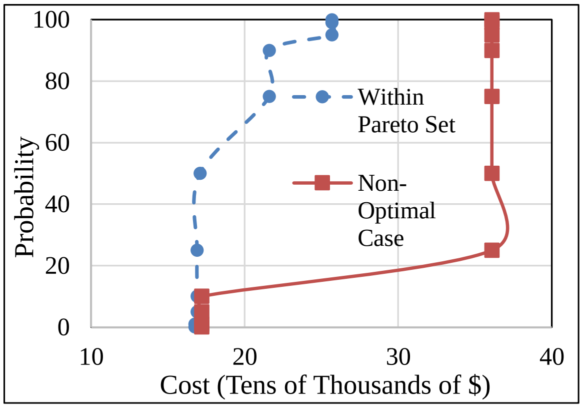
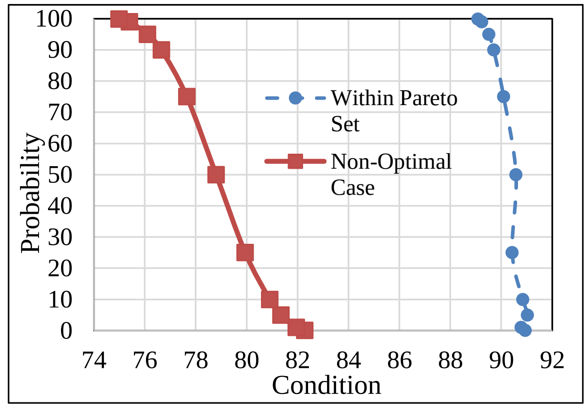


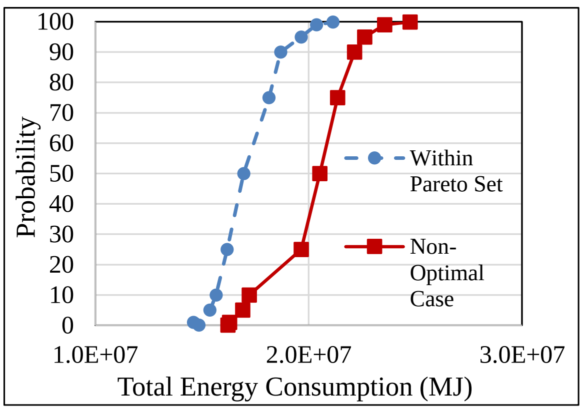
Figure 0-4 Probabilistic Consideration of Pareto Set

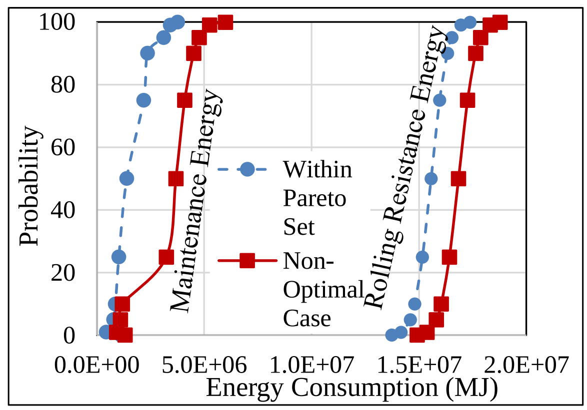
In order to evaluate the potential range of values when two maintenance plans are analyzed probabilistically over a three year period, one that yielded values that were contained in the Pareto set, as well as a plan that is not considered optimal, two maintenance plans were chosen and analyzed over a range of probabilities. The plan that was considered as optimal (i.e., contained in the Pareto set) consisted of maintaining Roads 2, 4 and 6 in the first year, Road 8 in the second year, and no roads in the third year. The plan that was not contained in the Pareto set (i.e., the Non-optimal case) consisted of maintaining Road 1 in the first year, Road 6 in the second year and Road 4 in the third year. The non-optimal case was chosen so that both condition and energy consumption could be made better for similar costs. The results of the cost, condition and energies as a function of their level of certainty (i.e., the cumulative probability such that $P(x \leq X)$) are shown in Figure 3-5a through Figure 3-5d.





(a) **(b)**





(c) **(d)**

Figure 0-5 Probabilistic Outcome for Maintaining Roads 2, 4 and 6 in Year 1, Roads 3, 5, 7 and 8 in Year 2, and No Roads in Year 3 (Within Pareto Set) and Road 1 in Year 1, Road 6 in Year 2,and Road 4 in Year 3 (Non-Optimal Case)

It can be seen in Figure 3-5 that the range of potential values of the maintenance plan that is contained within the Pareto set is consistently less than the range of values of the non-optimal plan. The large increase in costs for probabilities above 25 percent in the non-optimal case are due to the uncertainties in the condition values when road 4 and road 5 are maintained (i.e., as probability increases, the condition in year two and year three decrease such that a higher level of maintenance is triggered). This jump in values also corresponds to a jump in values for maintenance energy (Figure 3-5d).

1.8. Conclusions

This paper presented a method by which an agency can evaluate the energy consumption of their road network, as well as the energy attributed to potential maintenance actions probabilistically. The main benefit of a probabilistic assessment over a deterministic assessment is the ability to incorporate uncertainties in the analysis to determine how the level of detail of the information may potentially impact the outcomes of the decision process. Furthermore, it was clearly demonstrated in this paper that a probabilistic assessment should be used when the uncertainties in the models may be significant. Another benefit of the probabilistic assessment is to determine which set of variables require more detailed information prior to decision making, and assess the impact of small changes in variable uncertainties in the overall outcome.

Incorporating environmental considerations into transportation decision making is an integral part of sustainable decision making, and is being promoted as a way to help mitigated global climate change factors. To this end, an agency should evaluate whether the currently used optimization and decision making techniques will facilitate environmental and societal considerations as objectives instead of soft constraints or secondary considerations. The process demonstrated in this paper represents one of many methods that an agency can use to evaluate sources of energy consumption and the impact of management actions on the energy consumption of their road network.

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