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A Multi-Criteria Decision Analysis Technique for Sustainable Infrastructure Management Business Practices

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1.1. ABSTRACT

This paper presents a decision analysis technique to allow highway agencies to assess the tradeoffs between costs, condition and energy consumption. It is shown how the entire feasible solution space can be evaluated between multiple stakeholders with differing values to assess the desirability of the outcomes resulting from infrastructure management decisions. Furthermore, an example network-level analysis is presented using data from the Virginia Department of Transportation. The example analysis clearly shows a tradeoff between the most cost effective outcomes (i.e., minimizing the cost divided by the condition) and the outcomes where the cost is minimized relative to the condition, and how decision analysis should account for this tradeoff. The results of the method presented show that various pavement management alternatives can be represented in terms of desirability, and that this desirability can assist the decision maker with making decisions about performance goals and targets.

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1.2. INTRODUCTION

A key aspect of sustainable development is understanding the tradeoffs that exist between maintaining quality and cost effective infrastructure while also mitigating adverse impacts on social and environmental systems (ASCE 2012). However, many long term environmental and social impacts related to infrastructure still contain a relatively high level of uncertainty. As a framework to build policy decisions around high levels of uncertainty pertaining to environmental and social impacts, many countries have adopted versions of the precautionary principle (Gollier et al. 2000; Kriebel et al. 2001). The precautionary principle employs an anticipatory attitude towards irreversible and potentially harmful environmental and social impacts, such as the current rate of unsustainable consumption of non-renewable energy. The precautionary principle states that a lack of full scientific certainty should not preclude actions towards mitigating potential harms caused by actions resulting in such impacts. A major component of the precautionary principle is the idea that scientific uncertainties are resolved over time, and that policy makers should adapt their method of decision making such that they continually learn about and update the potential solution space regarding their specific objectives.

It has been proposed that a key component of the precautionary principle, an evaluation of an entire feasible solution space including all potential outcomes, can be applied to enhance sustainable development in the face of long-term uncertainties about adverse impacts (Steele 2006). Inherent in this approach is the idea that sustainable development must be evaluated as a multi criteria problem, and that policy makers should be presented with a solution space of many feasible outcomes, as opposed to a single optimal solution. Many researchers have proposed multi criteria decision analysis approaches with the goal of seeking an optimum, or most desirable solution given the tradeoffs in various infrastructure management criteria (Li and Sinha 2004; Zietsman et al. 2006; Smith and Tighe 2006; Stich et al. 2011). However, a method to present the entire solution space in terms of the optimality or desirability of various outcomes in relation to commonly used variables in infrastructure management (e.g., cost or infrastructure condition) has yet to be developed. In light of this, a method to evaluate and represent a multi criteria decision problem over an entire solution space is presented in this paper. The analysis is presented in terms of pavement management and energy consumption, but it is expected that the techniques presented will be applicable to many fields.

1.3. OBJECTIVE

The objective of this paper is to present a practical multi-criteria decision making technique for pavement management applications. The technique focuses on representing the desirability or optimality of a set of potential outcomes in terms of commonly used variables in pavement management (i.e., cost of maintenance and condition of the pavement). The variable used in this analysis to represent adverse environmental impacts is energy consumption. The anticipated benefit of the methodology presented in this paper is that it will result in an adaptive decision-analysis tool that policy makers can use to *learn* about feasible outcomes and the resulting impact of weights they place on certain variables (e.g., costs, energy consumption, etc.). It is also expected that the decision method presented in this paper will assist agencies in working with the public when setting policy decisions regarding tradeoffs to adverse environmental impacts, as recommended by the National Academies of Sciences (Dietz and Stern, 2008).

1.4. BACKGROUND

Sustainable pavement management is an emerging area of research that is concerned with maintaining acceptable condition of pavements while also considering the tradeoffs between cost, environmental impacts and social impacts of pavement investments. Generally the tradeoffs between economic, environmental and social factors require that (1) the agency in charge of managing pavements maintains an accurate database that includes the pavement condition and (2) models to predict the resulting impacts of pavement management decisions on each sustainability factor. Most efforts to date have focused on defining pavement sustainability and sustainable performance measures. However, a next critical step is implementing sustainability into the pavement management decision-making process. This includes incorporating sustainability as a fundamental business practice within the agency where considerations about project selection, treatment type selection, lifecycle management, and triple bottom line (economic, environmental and social) tradeoffs are addressed in the initial decision processes.

The multi-objective decision problem arising from sustainable pavement management is generally converted to a single objective problem by treating some of the objectives as the constraints (Wu and Flintch 2009). In this way, an agency seeks to maximize or minimize one particular objective (e.g., minimizing the cost divided by the performance of the pavement condition) subject to constraints that arise from the original objectives. A shortcoming with the single criterion approach is that when objectives are reformulated as constraints, the resulting analysis becomes non-compensatory (Goodwin and Wright 1998). In other words, undesirable values in the newly formulated constraints are no longer compensated for by highly desirable values in the objective values. Consequently, there is no longer a guarantee that the selected value is non-dominated, and a more optimal value may exist depending on the extent to which the constraints are relaxed. Secondly, the non-compensatory analysis tends to bias the results to the parameter that is chosen as the objective function, thus rendering other objectives as lower level considerations.

Many methods have been proposed for finding solutions to the multi-objective problems encountered in the transportation setting, such as utility theory (Li and Sinha 2004; Zietsman et al. 2006), the analytical hierarchy process (Smith and Tighe 2006) as well as rank aggregation methods when limited alternatives are presented (Stich et al. 2011). Each method has demonstrated advantages and shortcomings, and thus no widely accepted method has been adopted by the transportation sector. This paper will demonstrate a method for finding solutions to the multi-criteria problem posed by sustainable pavement management by combining the benefits cited for other proposed methods into the development of a novel new technique. Pavement management includes analysis at multiple levels, generally divided into the strategic level, network level and project level, which are described in more detail by Butt et al. (1994). The method demonstrated in this paper is expected to be most applicable to the network-level (e.g., for setting objectives for the project selection process) and strategic-level (e.g., for setting targets for performance levels). Therefore, the solution space is expected to be relatively large, and the direct comparison of alternatives may not be feasible.

1.5. MULTI-ATTRIBUTE DECISION ANALYSIS IN INFRASTRUCTURE MANAGEMENT

Given the multiple objectives presented in sustainable pavement management, an important tool to consider for applying sustainable pavement management in decision making is multi-attribute decision making. Important aspects in multi-attribute decision problems are multiple objectives (i.e., multiple criteria and desired levels of attainment for each criteria), constraints for the criteria and preference functions or weighting values used to compare the criteria. Solutions for multi-criteria problems are given by a set of non-dominated solutions (as opposed to a single optimal solution), and thus some judgment or preference function must be evaluated to select the preferred solution from amongst the non-dominated set.

Several methods exist for solving multi-attribute problems. For example, Wu and Flintsch (2009) present a method for replacing traditional deterministic constraints with stochastic constraints before developing the set of non-dominated solutions. Giustozzi et al. (2012) proposed a method of rescaling each criteria between zero and one, weighting each criteria in terms of preference, and then summing the product of each rescaled criteria and criteria weight to determine the best alternative. Li and Sinha (2004) presented a method for using utility theory in transportation asset management decision making. Another application of utility theory in transportation decision making was presented by Zietsman et al. (2006).

One important aspect of multi-criteria problems is the aggregation of preferences among many decision makers who might consider different solutions optimal. Identifying a preferred set of solutions using multi-criteria techniques can support more effective decision-making and promote learning among those engaged in the decision process. As an example, Stich et al. (2011) developed a number of proposed highway alignment alternatives using GIS tools, and then utilized a public informational meeting to have the voters rank the projects given all of the relevant information (i.e., wetland impact, noise and air pollution, etc.) about each alternative. Preference rank aggregation techniques were then used to combine the input to inform the final decision. One policy related benefit that the research cited about gathering the stakeholder's preferences was the possibility of streamlining project delivery times by addressing concerns of the public before they arise, instead of retroactively trying to mitigate the problems and concerns. Lahdelma et al. (2000) describes the use of ranking alternatives among the many stakeholders as an important key to environmental decision making.

Another example of ranking is the analytical hierarchy process (AHP). Smith and Tighe (2006) describe using AHP as a tool for assessing user preferences for maintenance or rehabilitation decisions in the context of transportation asset management. A large subset of road users were identified and surveyed to determine their preferences for many different criteria related to road maintenance and rehabilitation. The preferences were then aggregated by using a simple averaging technique, and the AHP technique was used to evaluate the criteria that were considered most important by user groups, and how the user groups would weight various alternatives.

1.5.1. Reference Point Programming

A multi-criteria technique that is used in business decisions is the reference point method, also known as reference point programming. Reference point programming falls within a family of decision analysis tools that also includes goal programming, where the programmers are attempting to minimize the deviation from the ideal solution (Romero et al. 1998). Reference point programming as described by Eiselt and Sandblom (2007) is a way of trying to maximize the distance between the worst outcome (or minimize the distance between the ideal point) and the many alternatives. Reference point programming shares many similarities with another common multi-criteria method, the Technique for Order Performance by Similarity to Ideal Solution (TOPSIS) method. In TOPSIS, the alternatives are ranked by comparing their distances to the most ideal solution, as well as their distances from the least ideal solution (Lai et al. 1994). One difference is that TOPSIS is a method that is used when finite alternatives are presented, whereas the reference point method is more readily generalized over a continuous solution space.

An advantage cited by Eiselt and Sandblom (2007) is that reference point programming provides an interactive method where the decision maker can assess the tradeoff at many points along the pareto frontier. One of the major advantages of reference point programminng is that the decision maker works directly with real values, as opposed to proxy values or weights (Bogetoft et al. 1988). Furthermore, given the interactivity of the reference point method, the decision maker is expected to learn about the problem during the process (e.g., the tradeoff between the variables becomes more evident) (Luque et al. 2009). One of the challenges with using reference point programming relates to the assesment of the distance function. Eiselt and Sandblom (2007) discuss how the optimal soultion is impacted by the use of the distance function, be it Euclidean (straight line) distances or other metrics, such as *Chebyshev* distances.

1.5.2. Utility Theory

Utility theory is a method in which a decision makers values are quantified over a range of feasible outcomes, then the values are combined with the corresponding probabilites of each outcome to form a set of utility values. The motivating factor behind utility theory is that if an appropriate utility is assigned to each possible outcome, and the expected utility of each alternative is calculated, the best alternative is the one that maximizes the overall utility (Keeney and Raiffa 1993). The strength of utility theory is that the relative scale of preference between possible outcomes for each variable is used to determine the best alternative from the set of possible alternatives. In other words, the range of values and differences in potential values are used to scale preferences. For example, it is not assumed that increasing a variable four times the original amount is preferred twice as much as increasing by two times the original amount.

Utility theory states that given an action a' that results in consequence x_i with a probability p'_i, we can determine a set of π_i's such that the decision maker is indifferent between the following two options (Keeney and Raiffa 1993);

1. Certain Option: Receive x_i with certainty
2. Risky Option: Receive x_n (best consequence) with probability π_i and x_1 (worst consequence) with probability (1- π_i)

Then the expected values of π_i's can be used to numerically scale the probability distribution over x_i's such that;

$$\bar{\pi}' = \sum_i p_i' \pi_i$$

Suppose we have two acts a' and a'' with associated $\bar{\pi}'$ and $\bar{\pi}''$, there is good reason to expect that the decision maker should rank the order of preferences of a' and a'' based on the values of $\bar{\pi}'$ and $\bar{\pi}''$ (Keeney and Raiffa 1993). Finally, the π's can be translated to u's by means of a positive linear transform such that the preferences for the probabilistic alternatives is maintained as follows:

$u_i = a + b\pi_i$ For b > 0 and i=1,2…n

For uni-dimensional utility theory, the consequence x_i describes one attribute, such as pavement condition. However, the condition of a transportation corridor is generally defined by many attributes taken together. Thus, multi-dimensional utility theory is employed, and the consequence x_i is used to describe multiple attributes in given states.

One drawback to utility theory is that proxy values (utilities) are used instead of real values, which opens the possibility of misconceptions between changes in real value and changes in utilities. Secondly, it is expected that since the objective is maximizing overall utility, the decision maker is biased to think that the corresponding alternative is optimal, instead of taking time to learn about other alternatives with high overall utilities.

1.6. PROPOSED METHODOLOGY

Drawing on strengths and drawbacks of the reference point method and utility theory, the proposed decision analysis method is a combination of the two methods. More precisley, it will be shown how the method introduces utility functions into the reference point method as an impedance field or a force field, and the distance vector can be described as the work required to go from the most desirable point (i.e., the reference point) to each point in the feasible set. The work represented in the decision analysis technique is the combination of the distance of any given point in the solution space from the most ideal point, and the value gained (in terms of utility) by travelling to the given point on the solution space from the most ideal point.

First the problem can be stated as;

$$\mathbf{Min}\left[y_1, y_2 ... y_k\right], \textit{for } k = 1, ... q$$

Where y are the values for k objective functions. It will be assumed for this case that the feasible set was determined satisfying all constraints (e.g., any solution alternative can be achieved with given budget), and contains the set of non-dominated (Pareto) points. A reference point can be described as the most desirable outcome from the point of view of the decision maker for each objective as:

$$y^* = \left[y_1^*, y_2^* ... y_k^*\right]$$

An example of a reference point given cost and condition is [0, 100], where zero represents no cost and 100 represents perfect condition. Although this is not achievable in practice, it is defined as the most desirable outcome. Given y and y^*, each feasible outcome (y) can be compared to the most desirable outcome (y^*). Traditionally, the objective of reference point programming is written as:

$$\mathbf{min}\, d(y, y^*)$$

Where d is a distance function, generally taken as one of the p-norm distances such that:

$$d(y, y^*) = \left(\sum_{k=1}^{q} \left|y_k - y_k^*\right|^p\right)^{1/p}$$

Where a value of p equal to two gives the Euclidean distance. However, defining the distance vector in terms of the work required to move through a field (Corwin and Szczarba 1995) yields:

$$d(y, y^*) = \int_{y^*}^{y} \mathbf{F}(\alpha(t)) \cdot \alpha'(t)\, dt$$

Where $\mathbf{F}(\alpha(t_i))$ is the magnitude of the field at location α and t_i defines the interval over which the sum is taken such that $0 \leq i \leq m$. The field at location α can be described using the utility functions evaluated at location α in the direction opposite of the vector defined by $(\alpha(t_{i-1}), \alpha(t_i))$. The distance function can be numerically approximated by:

$$d(y, y^*) \approx \sum_{i=1}^{m} \left[\mathbf{F}(\alpha(t_i)) \cdot \alpha'(t_i)\right](t_i - t_{i-1})$$

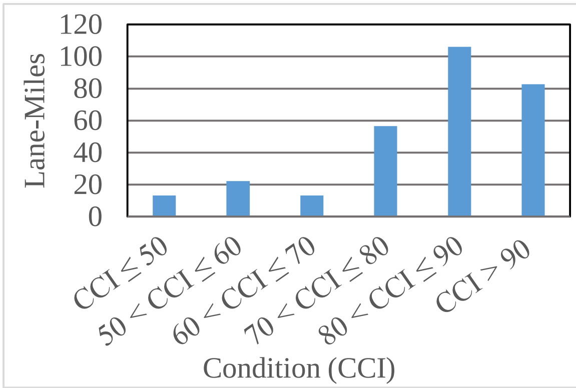
Two important concepts must be addressed at this point. First, the utility functions should be scaled such that the maximum utility value corresponds to the least desirable choice so that the maximum work vector corresponds to the least desirable alternative. This is because the work done is a product of the force applied to the vector and the total distance travelled along the vector. Secondly, the values for each variable and utility values should be scaled similarly so that neither dominate the analysis. This will be demonstrated futher in an example analysis.

1.7. Analysis Using Cost, Condition and Energy Consumption of a Road Network

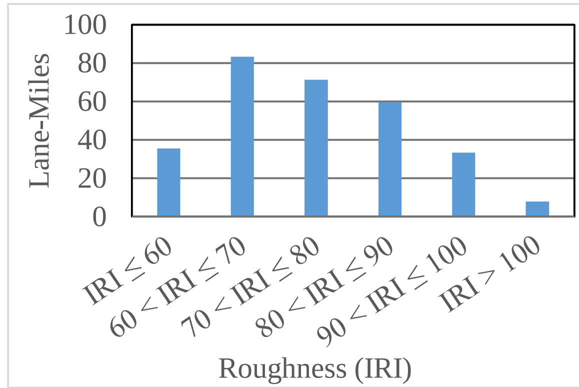
In order to demonstrate the concept discussed in the previous section, an example problem will be presented. Three objectives will be considered in this example as follows:

$$\left[\mathbf{Min}(\mathbf{Cost}), \mathbf{Max}(\mathbf{Condition}), \mathbf{Min}(\mathbf{Energy})\right]$$

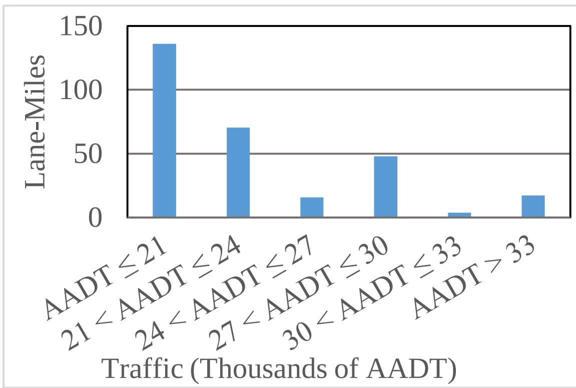
The data for this example was obtained by analyzing a subset of flexible pavements along Interstate 81 in the Virginia Department of Transportation’s (VDOT’s) Salem District. The total length of the pavements was approximately 291 lane-miles (468 lane-km), and the pavements were broken into 65 different segments, ranging in length from 0.5 lane-miles (0.8 lane-km) to 16 lane-miles (26 lane-km), based on the segments defined by the 2012 VDOT pavement management system (PMS). The condition and roughness data was obtained from the VDOT PMS for each pavement segment. The condition was reported in terms of the Critical Condition Index (CCI), a value ranging from 0 (impassible) to 100 (perfect condition). The roughness was reported in terms of the international roughness index (IRI). Finally, the traffic was obtained from the VDOT traffic count website, where it is stored in Microsoft Excel files, and the traffic in terms of average annual daily traffic (AADT) and percent trucks was extracted for each pavement segment. Summary plots of the traffic, CCI and pavement roughness (in terms of IRI) are shown in Figure 0-1.



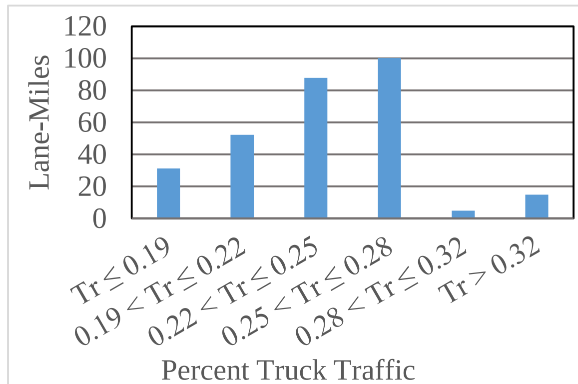
(a)



(b)



(c)



(d)

Figure 0-1. Network Condition, Roughness and Traffic Data

1.7.1. Multi Year Analysis

A five year network level analysis was conducted on the pavement network to determine the cost, average condition and energy consumption resulting from a range of different maintenance actions. The maintenance actions were based on VDOT (2011), and defined as Do Nothing (DN), Preventive Maintenance (PM), Corrective Maintenance (CM), Restorative Maintenance (RM) and Reconstruction/Rehabilitation (RC). The maintenance actions were triggered based on condition, such that pavements with condition greater than 90 were set as DN, PM was triggered at condition less than 90 and greater than 80, CM was triggered at condition less than 80 and greater than 65, RM was triggered at condition less than 65 and greater than 45, and RC was triggerred at condition less than 45. It was assumed that PM did not impact pavement roughness, and that the condition was increased by 8 points, which adds approximately 3 years of life within the condition range specified. When CM, RM and RC were applied, the IRI was set to 55 in/mile (0.87 m/km) and the CCI was set to 100.

The deterioration model used for the pavement condition was taken from the model used by the VDOT PMS as discussed in (Stantec and Lochner 2007). IRI growth was assumed at 5 in/mile/year (0.08 m/km/yr). This is higher than the mean value reported by McGhee and Gillespie (2006), and is closer to the value representing a 95 percent certainty given the data reported. The expected energy consumption for each of the maintenance actions was taken from Bryce et al. (2014). The energy consumption due to the vehicles was taken as a function of the IRI, and the models developed by Chatti and Zaabar (2012) were used to obtain the fuel consumption values. Finally, the expected costs for each maintenance action was obtained from VDOT (2011).

1.7.2. Analysis Methodology

In order to obtain the range of energy consumption, average condition and cost values for the five year analysis of the pavement network, a non-linear binary optimization program was set up in MATLAB™. The objective of the optimization was to minimize the energy consumption for given targets of cost and condition throughout the feasible solution space. The problem setup was similar to the methodology presented by Smadi and Maze (1994), with the exception that pavement roughness was also a variable that was tracked. Therefore, the procedure was: (1) determine the condition of the pavement given the pavement age; (2) determine the appropriate treatment given the condition; (3) determine the condition and pavement roughness in the year following the treatment given the treatment type; (4) determine the energy consumption value and cost associated with the treatment type and (5) determine the energy consumption due to the vehicles travelling along the pavement as a function of the pavement roughness, number of trucks and total AADT. Mathematically, the binary optimization of the energy consumption values can be expressed as:

$$e_i^j = F\left(X_i^j, Y_i^j, CCI_i^j, IRI_i^j\right)$$

Where e_i^j is the energy consumption attributed to pavement section *i* in year *j*, X_i^j is the binary variable representing whether pavement section *i* is selected for treatment in year *j*, Y_i^j is the binary variable representing whether pavement section *i* is selected for PM in year *j*, CCI_i^j is the condition for pavement section *i* in year *j*, IRI_i^j is the roughness for pavement section *i* in year *j*.

Finally, the genetic algorithm tool built into the MATLAB™ global optimization toolbox was used to find the non-dominated surface that relates cost, condition and energy consumption. A discussion of genetic algorithms as they relate to pavement management can be found in Pilson et al. (2007) and Gao and Zhang (2008). The resulting pavement surface is shown in Figure 0-2.

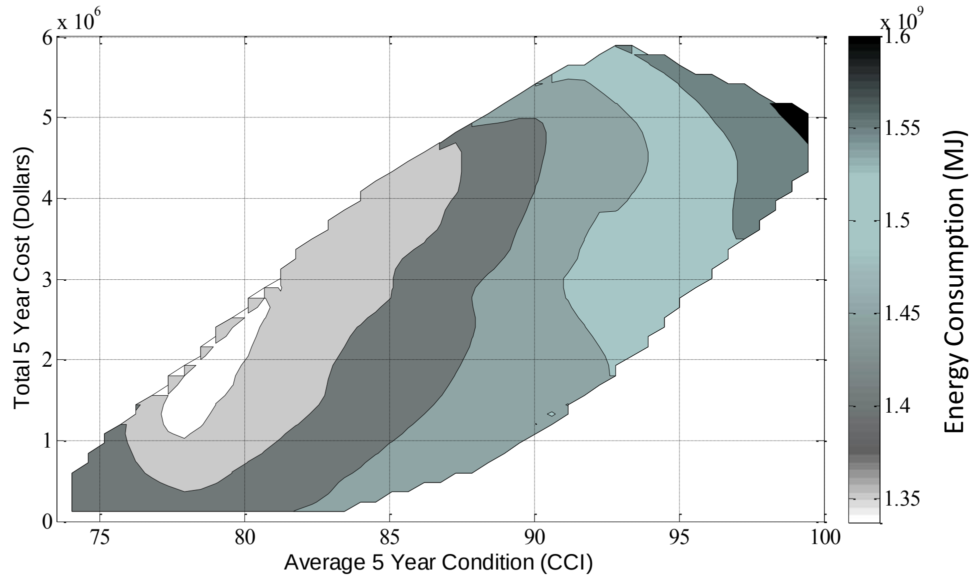


Figure 0-2. Solution space With Energy Consumption (MJ) as the Elevation Contour

The first thing to note from Figure 0-2 is that the range of condition in which the energy consumption is minimized (i.e., a CCI of 77 to 82) includes the current weighted averaged condition of the pavement network (81.4). Furthermore, if the pavement is allowed to deteriorate for the first year with no intervention, the weighted average condition for the second year becomes 76 (assuming VDOT's deterioration model), which falls outside the range of minimizing the energy consumption. With no work performed, the condition of this pavement network would fall to 67, and the energy consumption (which would consist purely of rolling resistance energy) would be $1.44x10^9$ MJ. Secondly, the minimum energy consumption does not follow the contour with the best cost benefit (i.e., the contour defining the lower bound of the solution space).

1.7.3. Applying the Decision Analysis Technique

The first step will be to rescale each variable for the j^{th} alternative such that they fall between zero and one, and define proxy variables for *x, y* and *z* such that the most desirable point (also called the utopia point (Luque et al. 2009)) corresponds to values of *x, y* and *z* all equal to zero (and the least desirable corresponds to a value of 1);

$$x_j = \frac{\text{Energy}_j - \text{Energy}_{\text{Utopia}}}{\text{Energy}_{\text{Max}} - \text{Energy}_{\text{Utopia}}}, y_j = \frac{\text{Condition}_{\text{Utopia}} - \text{Condition}_j}{\text{Condition}_{\text{Utopia}} - \text{Condition}_{\text{Min}}}, z_j = \frac{\text{Cost}_j - \text{Cost}_{\text{Utopia}}}{\text{Cost}_{\text{Max}} - \text{Cost}_{\text{Utopia}}}$$

Note that one valuable benefit of rescaling each value such that the utopia point corresponds to *x, y* and *z* all equal to zero and keeping the interval constant is that the work vector is always beginning at values of zero, thus $\alpha(t) = ((t_x - t_{x-1}) + t_x, (t_y - t_{y-1}) + t_y, (t_z - t_{z-1}) + t_z) \approx (0 + t_x, 0 + t_y, 0 + t_z)$, and $\alpha'(t) = (1,1,1)$. The reference point was chosen as 100 for condition, 0 for cost, and 0 for energy. Next, the vector of the force field that is directly counteracting the vector defined by (*y, y**) can be described as $\mathbf{F}_j = (u_E \rho_j, u_C \beta_j, u_M \gamma_j)$ where u_E, u_C and u_M are the utility functions corresponding to energy, condition and cost (respectively), and;

$$\rho_j = \frac{x_j}{\sqrt{x_j^2 + y_j^2 + z_j^2}}, \beta_j = \frac{y_j}{\sqrt{x_j^2 + y_j^2 + z_j^2}}, \gamma_j = \frac{z_j}{\sqrt{x_j^2 + y_j^2 + z_j^2}}$$

The utility functions used in this case were assumed, and were developed such that the decision maker is risk neutral towards increases in energy consumption, slightly risk averse towards condition and relatively highly risk averse for cost (Figure 0-3). The utility functions were then rescaled such that the least preferable option corresponded to the highest utility value. Finally, the work required to travel from the utopia point (chosen as the reference point) to the location of each of the alternatives was calculated and the results, along with the contour plot representing the alternatives, are shown in Figure 0-4. The results in Figure 0-4 are representative of the case that cost, condition and energy consumption are weighted equally.

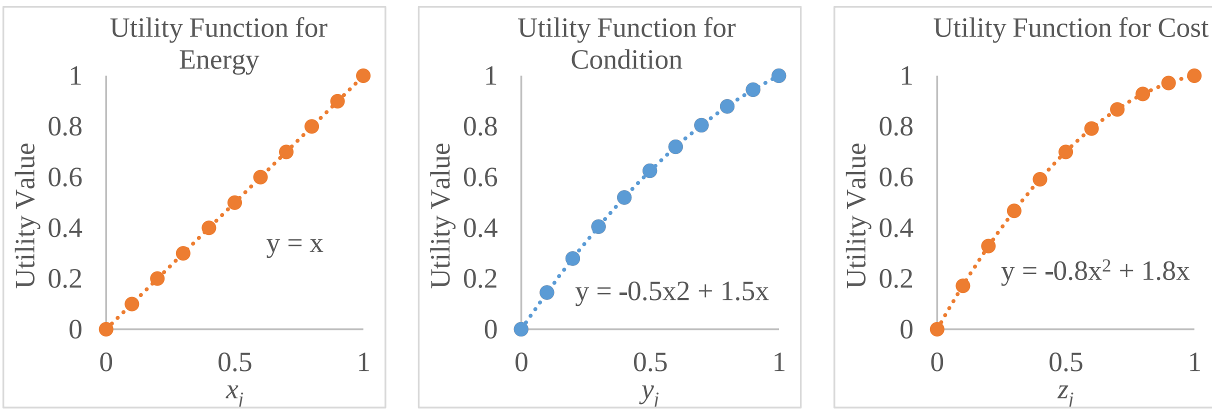


Figure 0-3. Utility Function Assumed for Example Analysis

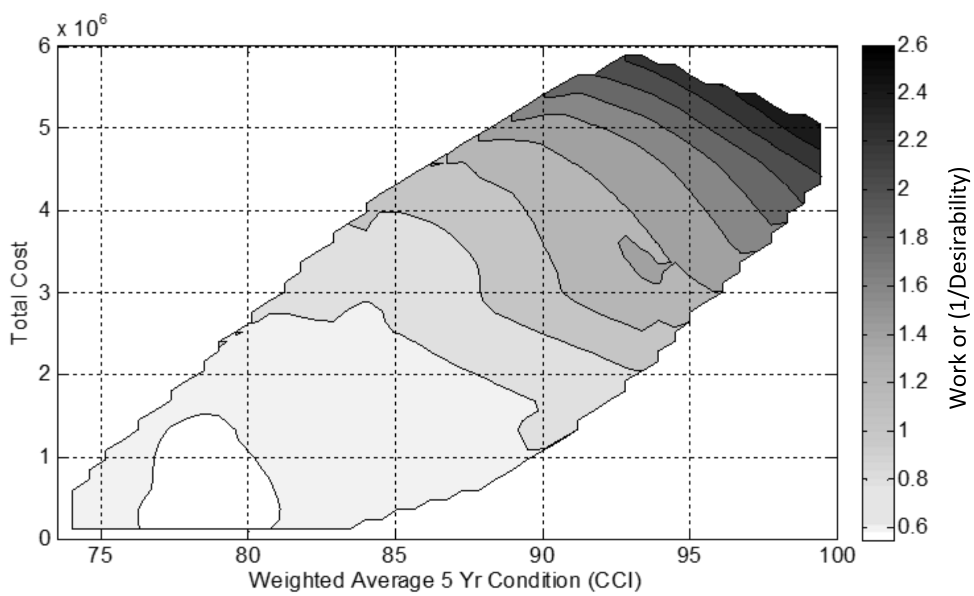


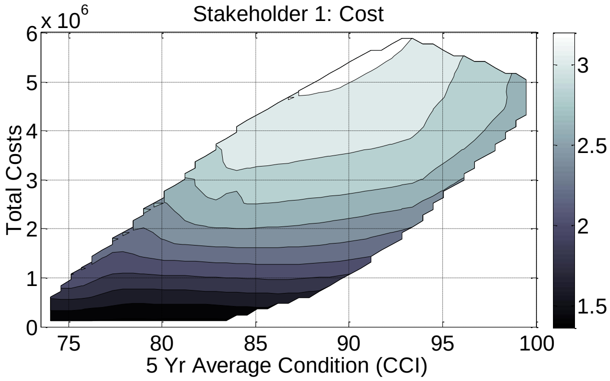
Figure 0-4. Contour Plot of Work Representing the Desirability of the Alternatives, Lower Elevations Represent Greater Desirability

It can be seen from Figure 0-4 that the options representing the minimum work (i.e., the most desirable alternatives) follow very closely to the contours representing minimizing energy consumption. This is because the costs are also relatively low for the alternatives with low energy consumption, even though the condition is also relatively low. Recall that, the condition of this pavement network would fall to 67 with an energy consumption of 1.44×10^9 MJ (purely due to rolling resistance) with no maintenance performed throughout the five year time frame. This energy consumption is approximately eight percent higher than the minimum energy consumption case (with the worst case being approximately 19 percent higher than the minimum energy consumption case). Thus, some maintenance is required to reduce the rolling resistance. However, as the extent of the maintenance performed over the five year time frame is increased, the benefits from the marginal reduction in energy consumption due to rolling resistance are negated by the increased energy consumption due to maintenance actions. Even though the total energy consumption due to the use phase far exceeds that of any other phase, the net energy consumption (i.e., the energy consumption of pavement with high rolling resistance minus the energy consumption of pavement with low rolling resistance) must be used when comparing potential maintenance strategies. This is because vehicle fuel consumption can only be reduced by a marginal amount by reducing rolling resistance, assuming the same type and number of vehicles in the before and after case.

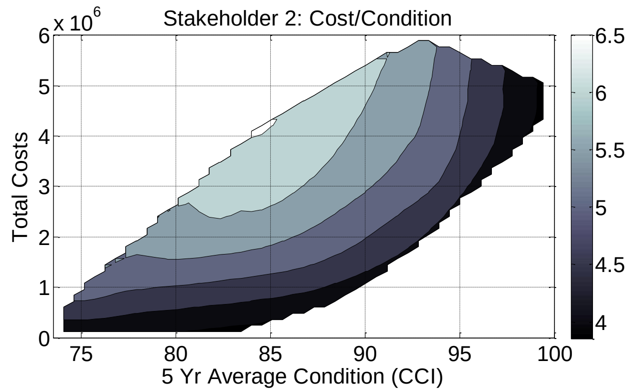
By representing the solution space as a continuum, it can be seen that the level of desirability for the alternatives changes as a function of costs incurred and average condition. Finally, the representation of the desirability of outcomes (Figure 0-4) is represented relative to cost and condition, which are two variables that are nearly ubiquitous among pavement management personnel, meaning that the impact of decisions (and variability of the desirability of possible outcomes) can easily be discussed among many people with little loss of information.

1.8. COMPARISON OF MANY STAKEHOLDERS

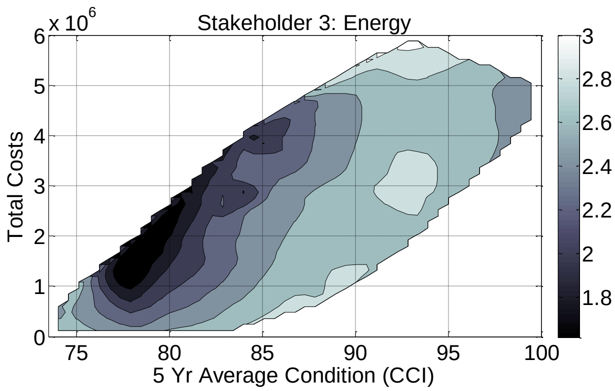
The results shown in Figure 0-4 represent the desirability of all potential outcomes, given a decision maker with specific preference functions (Figure 0-3) and equal weights for all criteria. Given the framework from the previous example, it is possible to represent the most desirable outcome of many stakeholders on the same figure. In this example, four stakeholders were assumed to all have the same risk preferences (given in Figure 0-3). The primary concern was minimizing cost for stakeholder 1, minimizing cost while maximizing benefit for stakeholder 2, minimizing energy consumption for stakeholder 3 and maximizing condition for stakeholder 4. The AHP (Saaty 1980) was used to elicit weights for each of the criteria. Stakeholder 1 is assumed to consider cost moderately more important than condition and strongly more important than energy, while considering condition moderately more important than energy. Stakeholder 2 is assumed to consider cost and condition equal with both strongly more important than energy consumption. Stakeholder 3 is assumed to consider condition as important as energy, condition moderately more important than costs and energy consumption strongly more important than costs. Stakeholder 4 is assumed to consider condition moderately more important than costs and strongly more important than energy consumption, while considering cost strongly more important than energy consumption. The resulting plots of work (with minimum work representing maximum desirability) are given in Figure 0-5.



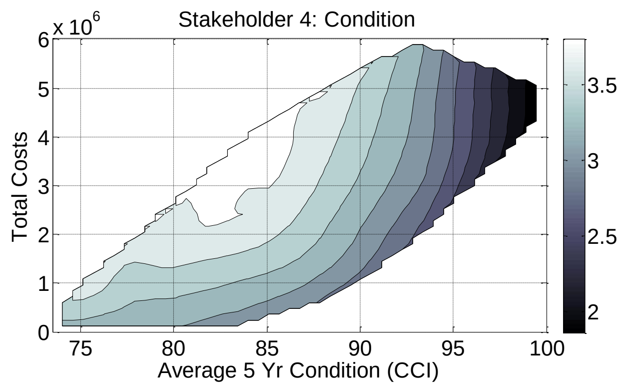
(a)



(b)



(c)



(d)

Figure 0-5. Desirability from Stakeholders, Lower Elevations Represent Greater Desirability

1.9. DISCUSSION

The different preferences among stakeholders can clearly be seen in each plot in Figure 0-5. For example, stakeholder 2 (Figure 0-5(b)) considered costs and condition equal while considering energy consumption of considerably less importance. Therefore, the plot of desirability of stakeholder 2 follows contours associated with the most cost effective strategies (i.e., minimizing costs divided by average condition). However, stakeholder 3 considers energy consumption the most important factor, and thus Figure 0-5(c) follows closely with Figure 0-2 in that the strategies that minimize energy consumption are the most desirable. Revealing stakeholders preferences in this way could promote learning among those engaged in the decision-making process, as well as help facilitate public involvement when developing policies regarding tradeoffs of environmental factors. As individuals begin to comprehend the broader implications of their preferences, these preferences may change as a deeper appreciation of the decision landscape emerges. Further, the data (or contour plots) from this approach could become ‘boundary objects’, mechanisms that promote “dialogue, information sharing, learning and consensus-building across different policy boundaries: between experts and non-experts, formal government and different nongovernment actors, higher-order governments and lower-order governments” (Holden 2013, p. 89).

An important implication of representing the decision space in terms of desirability among many stakeholders is that the agency can directly evaluate how the final decisions vary from the preferences of the stakeholders. It is clear in Figure 0-5 that the tradeoffs that are inevitable in the final decision made by the agency can only be seen as optimal by a maximum of two of the four stakeholders. In other words, if an optimal decision is chosen from one of the plots in Figure 0-5, at least two of the stakeholders will not see the final outcome as optimal. Furthermore, visualizing the tradeoffs of many stakeholders can serve as a platform for informing change within the agency, in terms of the agencies strategic goals and objectives. This is because many transportation agencies are in charge of managing public assets, and the goals and objectives of the agency must reflect the goals and objectives of the travelling public. Finally, it is possible to combine all of the stakeholders on one plot by calculating the average work to get to each point in the solution space. It was assumed that all stakeholders are weighted equally. The results are shown in Figure 0-6, where the lowest elevation represents the most desirable combined outcomes for all stakeholders.

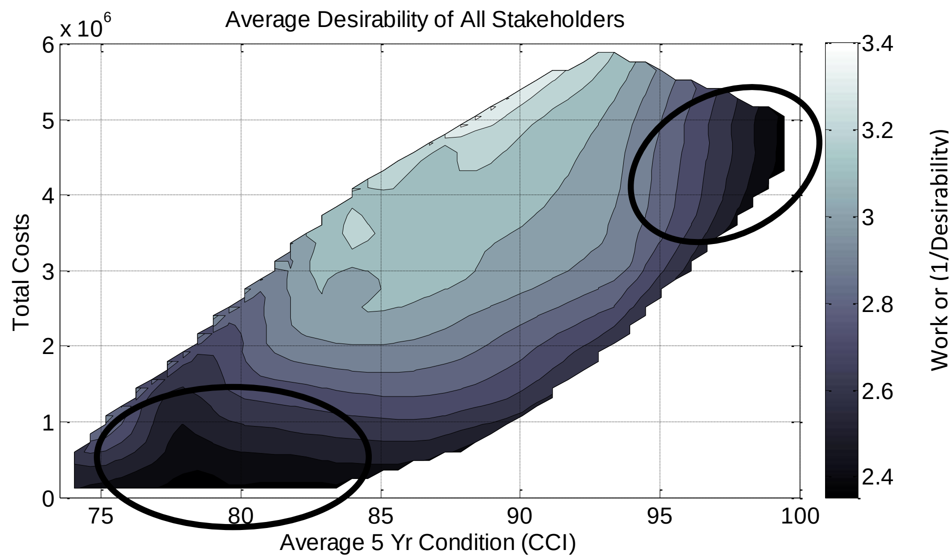


Figure 0-6. Average Desirability from Stakeholders, Lower Elevations Represent Greater Desirability

From the results in Figure 0-6, it can be seen that any optimal decision strategy should be chosen so that the total 5 year costs fall below 1 million dollars, or the average 5 year condition falls above 95. Furthermore, it can be seen in that the optimal sets of outcomes for the given set of stakeholders follows the most cost effective outcomes. This can be attributed to the fact that three of the four stakeholders weighted their most desirable outcome as one which falls along the contour also defined by the most cost effective outcome (Figure 0-5).

1.10. CONCLUSIONS

The decision analysis technique presented in this paper provides decision makers with the tools necessary to support complex, multi objective problems while also learning about the tradeoff by evaluating the solution space for the variables of concern among many stakeholders. One important finding in this paper is that the most cost effective maintenance alternatives may tend to correspond to alternatives with a much higher level of energy consumption than the maintenance alternatives not considered the most cost effective (in terms of only cost and condition). This is because a tradeoff exists between the energy consumed when maintenance actions are performed and the energy consumed by vehicles travelling on the pavement (which increases with increasing pavement roughness). Preventive maintenance actions are known to be a less energy intensive and a more cost effective treatment, which does not improve pavement roughness or the energy consumed by vehicles travelling on the pavement. Therefore, a decision maker who is more concerned with cost effectiveness may tend to employ more preventive maintenance activities than a decision maker who also takes environmental considerations (e.g., reducing energy consumption) into account.

The proposed decision analysis technique advocates the evaluation of the entire solution space which presents many potential benefits, including providing the ability to combine the desirability of the outcomes for all potential solutions (as opposed to only optimal solutions) for many stakeholders. Secondly, by visualizing the solution space for each stakeholder, those engaged in the decision-making process have the opportunity to understand the relationship between their preferences and the viability of potential solutions. This feedback may result in the adjustment of preferences based on a deeper understanding of the tradeoffs, promoting a dynamic process that better reflects real-world decision making. Furthermore, decision-makers could evaluate the impact of potential outcomes on certain stakeholders, and potentially modify the weights given to particular attributes based on this. By considering how all stakeholders view the tradeoffs in the feasible solution space, as opposed to only evaluating optimal outcomes among the many stakeholders, a more complete assessment can be made of which solutions are likely to receive broad support and, thus, less resistance in their implementation.

It has long been recognized that decision making within pavement management includes tradeoff between many competing objectives (Wu and Flintsch 2009; Gurganus and Gharaibeh 2012), as well as between many stakeholders (Smith and Tighe 2006; Stich et al. 2011). Furthermore, environmental considerations in pavement management such as reducing overall energy consumption have come to the forefront of concerns in recent years (FHWA 2014). To address these considerations, new business practices will have to emerge in pavement and infrastructure management for policy and decision makers, and public engagement must also be considered as a factor when setting policies (Dietz and Stern, 2008). This paper represents one step in the process towards more sustainable pavement management business practices.

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